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# LIGHT

## AN ELEMENTARY TREATISE

BY

SIR HENRY TRUEMAN WOOD, M.A.,

SECRETARY OF THE SOCIETY OF ARTS.

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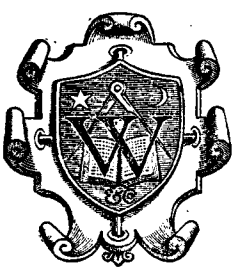

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# PREFACE.

IN the treatment of the present subject it has been thought desirable not to assume any previous knowledge on the part of the reader, or any familiarity with mathematical methods.

The book has throughout been written with the view of providing such information as an intelligent student unfamiliar with natural science would require, and it is hoped that the information has been given in a sufficiently simple form; but no attempt has been made to adopt the language or the style which would naturally be used in a book specially intended for young people.

As to the contents of the book:—An explanation is given of the modern theory of light, and an attempt made to show how the various phenomena which are matters of common observation can be explained on that theory. The nature of colour and the manner of its production are described; a brief account is given of the more important optical instruments, and the principles of their action. In a chapter on the chemical effects of light, an explanation is provided of those permanent alterations produced by light, which find their most striking application in photography; while to make the outline fairly complete, a short description is added of the phenomena produced by polarized light, and also by fluorescence.

It may be thought that some apology is due when one who is not a professed authority on a scientific subject, and cannot claim to have assisted its progress by original research, comes forward to instruct others in that subject. If however this little book serves its purpose, no apology is required. If it fail to do so, no apology will be of any avail.

This much qualification the writer may indeed claim, a thorough familiarity with the difficulties which beset the path of those humbler students of science who can devote their leisure only, not their working life, to their favourite pursuit.

And as such a one must of necessity view a subject from a different standpoint from that of those who have mastered its intricacies, and whose occupation it is to extend its boundaries, he may perhaps have some justification for an attempt to act as guide to those who are in like case with himself, and desire to obtain some knowledge of the workings of Nature, even though they may not have the opportunity, or perhaps the capacity required for following those workings to the limits of our present knowledge.

In a book of this sort, which professes only to be a summary of the work of previous writers, it is but honest that due acknowledgment should be made of the amount of indebtedness. The writer has thought that such acknowledgment can be most fitly and most usefully made in the form of an Appendix, giving the names of those books which, as they have been most serviceable in his own studies, will probably be most useful to other similar students.

Special thanks are however due to the publishers of

"Weinhold's Experimental Physics" (Messrs. Longmans) for permission to reproduce a number of illustrations, including especially those used in Chapters II, and VII., to illustrate the action of curved mirrors and of lenses, and in Chapter VIII., to explain the principles on which optical instruments are constructed.

The writer is also indebted to Messrs. Macmillan for the loan of the woodcut on page 48, explanatory of the phenomenon of mirage. It is taken from Guillemin's "Forces of Nature."

H. T. W.

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*Ὄψις δὴ κατὰ τὸν ἐμὸν λόγον αἰτια τῆς μεγίστης ὠφελείας γέγονεν ἡμῖν.*

PLATO, *Timæus* 47 A.

# LIGHT.

## CHAPTER I.

### THE NATURE OF LIGHT.

What is Light?—The Corpuscular Theory.—The Undulatory Theory.—Wave Motion.—The Ether.—Rectilinear Transmission of Light.—Formation of Images.—Shadows.—Law of inverse Squares.—Photometry.—The Speed of Light.

THE question, "What is Light?" is one that can be answered—scientifically—to the perfect satisfaction of anybody who already possesses the knowledge. It is by no means easy to reply to it in such fashion as to be understood by those who ask it, as questions are generally asked, for the sake of obtaining information.

Now the only person who can answer questions of this sort is Nature, and we may be pretty certain that if we put the questions rightly we shall get true replies. Unhappily Nature is like the Delphic oracle of old. Her answers are what the Greek poet called φωνᾶντα συνετοῖσιν, intelligible only to the wise, and in many cases capable of more than one interpretation. It is therefore only by a persistent course of cross-examination, by bringing together and comparing evidence bearing on the facts we desire to discover, and so ascertaining where the greatest amount of evidence—often apparently con-

tradictory—lies, that we can find out the truth about any natural phenomena.

As to the means of inquiry, since, unlike the Delphic oracle, Nature remains an abstract personality to whom no direct demand for information can be addressed, we have but observation and experiment—observation of the recurring phenomena of nature, and the experimental examination of such of those phenomena as we can reproduce under conditions favourable to the particular inquiry we are bent upon, and as far as possible isolated from surroundings likely to obscure or confuse that inquiry. In some sciences we must rely on observation mainly; in others on experiment. Astronomers must be content to observe the movements and characters of the heavenly bodies. They must wait years for a transit of Venus, centuries for the recurrence of a comet. On the other hand, the chemist produces the phenomena which he investigates, and accumulates knowledge as to the nature and properties of various bodies, by constantly subjecting those bodies to new conditions and noting their behaviour under such conditions.

Since then we can get no direct answer to our interrogatories, our only way is, like the skilful detective, to form some one or more hypothesis which may account for the observed facts, and to go on observing more facts until the balance of evidence leans so far in favour of one or other hypothesis that it can be adopted, to the exclusion of the rest. If it is found not to be inconsistent with any of the observed facts, it then takes rank as a theory, and holds the field as an explanation of those facts, unless or until some other theory is found giving a better and more probable explanation of them.

So has it been with the phenomena of Light. There are, or were, two theories to account for them. Of these the older was put in its crudest form by Lucretius, who conceived that all objects were continually throwing off thin shells or images of themselves, which images, being received in the eye, were the cause of vision. The theory is obviously incomplete, and indeed is meant to explain how it is we see things, and not how the phenomena of light are produced. Indeed the first objection to it that occurs is, that if it were true we ought to see as well in the dark as in the light, unless it were further assumed that the emanation only happened when light (whatever light might be) was acting on the body.

The corpuscular or emission theory of light proper was a much more advanced conception. It assumed that luminous bodies are continually discharging in every direction inconceivably minute particles. These particles entering the eye, whether direct from the luminous body, or after reflection from surrounding objects, produce the sensation of vision. According to this theory, therefore, we see a candle-flame because when we look at it our eyes are bombarded with an infinite number of particles, starting from every point of the flame, and therefore forming in the eye an image of the flame. If there happens to be a book lying near the candle, the book also has a similar shower of particles poured upon it; these are reflected in all directions, and a certain number are directed to the eye, enter it, and produce therein an image of the book.[1]

This theory was for a long time accepted as sufficient

[1] For the moment we are not concerned with the manner in which, by the mechanism of the eye, the image is formed.

explanation of the observed facts, and it sufficed even for the illustrious Newton, though it has been said that his belief in it retarded for long the progress of optical science. It, however, appeared to be inconsistent with certain phenomena, and as the science advanced it became evident that it was irreconcilable with some demonstrated facts, and that therefore it could not be true. As is usual with scientific theories, it struggled hard for existence. It was supported by many leaders of scientific thought, until it was at last compelled to give way to the more modern theory, the *undulatory* theory of light.

Now it will not be unfair, and it may simplify our ideas, if we consider the *undulatory* theory rather as a development of than as an opposition to the *corpuscular* theory. They are indeed both *emission* theories. From every luminous source, whether it be the sun, a star, an electric lamp, or a candle, *something* is sent forth which proceeds straight to our eyes, enabling us to perceive the source of light. The older men of science not unnaturally considered that something to be a material particle. The particle was imponderable, it had no weight, it was transmitted with extreme velocity; some thought that, outside the limits of our air, it was instantaneously transmitted, that its passage from a distant fixed star to the earth was effected without any lapse of time; it was in fact endowed with all the characteristics necessary to enable it to act as it was believed to act, but it was a material something.

According to the newer theory, the something which is emitted from the luminous source is not a material but an impulse. Perhaps an analogous case may make this

clearer. When the bow is drawn over the strings of a violin we hear a sound, but no material substance flung off from the string strikes the ear. We know quite well what does happen. The string is caused to vibrate. Its movements communicate to the particles of air surrounding it a tremulous movement like its own. These in their turn pass the movement on, and what we know as a wave of sound radiates out in every direction from the point where the action was first started. And it must be remembered that nothing moves except the wave itself. There is no current of air, there is no movement of the air except the trembling motion, to and fro, of the separate particles.

With water we can get visible waves, visible at all events on the surface. A stone dropped into still water produces circles of ripples. Each ripple passes swiftly over the surface of the water, but there is nothing like a stream of water flowing from the point of disturbance. The particles of water simply rise and fall, as is shown by the movement of any little floating matter on the surface, and the collective symmetrical movement produces the wave.

Or consider the effect produced by the wind on a field of growing corn. Each puff of wind, as it passes on, depresses the mass of cornstalks, which rise again after its passage. Here again we get a wave, while it is certain no single stalk has shifted its actual position.

With these analogies in mind, it will not be difficult to conceive the idea of an impulse being transmitted from a certain source without involving any beyond a vibratory or tremulous movement in the medium through which it is propagated, or to understand that the phenomena of light may conceivably be explained by the trans-

mission of such an impulse merely, as readily as by the older notion of the transmission of material particles. That this is so may be taken as at present a generally accepted fact, while it is also possible to go further, and to say that certain phenomena, readily explicable by the new theory, are quite inexplicable by the old, and that by its aid other phenomena have been anticipated which have afterwards been observed. It is true that there yet remain other facts not easy to reconcile with the theory, though none actually irreconcilable with it.

But at the outset we meet with a difficulty. Suppose it to be admitted that light is transmitted by means of vibrations—what is it that vibrates? It is not the air. Light reaches us from limits far beyond the bounds of the atmosphere, and it passes freely through substances which contain no air—glass for instance. To meet this difficulty physicists have adopted—with modifications—the old idea of a luminiferous ether, a substance infinitely thin and subtle, pervading all space, without weight, capable of transmitting luminous vibrations.

As this idea is very abstruse, and not easily intelligible to those who are not familiar with scientific thought, it may be sufficient here to say that there does exist actual evidence of the existence of the ether, but that at present it is merely admitted as a convenient assumption. It is certain that light is produced by the vibrations of some medium. That medium must possess the characteristics which scientific investigators have attributed to the ether. They have therefore assumed the existence of a medium with those characteristics. Future investigations may relegate the luminiferous ether to that limbo where repose phlogiston and many of the conceptions of

former workers in science, conceptions which in their turn have served as useful instruments of research, even though the investigations they have aided have but served to destroy them, or rather to replace them by ideas more consonant with increased though far from complete knowledge. At present, however, as its existence is assumed, on evidence sufficient to satisfy those best qualified to judge, humbler students of science may be content to acquiesce in the theory, at all events until they have acquired sufficient knowledge to disprove or to improve it.

Perhaps the first, the most easily recognizable property of light, is that it moves in straight lines. That this is so may be roughly shown by many simple experiments. The rays of light shining in at a window mark their path among the dust and motes suspended in the air in perfectly straight lines; the beam from a lighthouse, or from the homelier policeman's lantern, is obviously to all human perception absolutely straight. But more than this, a moment's thought shows us that if we point a telescope at a distant object it is only in order that the light coming from the object may strike directly into the telescope and so into the eye, or that it is because the light comes in straight lines from the target or the bird that the marksman is able to direct his rifle at the target, or the sportsman his gun at the game before him. So too it is on this property of light that all our surveys are based. The imaginary triangles which are described over the face of the country before it can be represented on a map are drawn in rays of light, the only straight lines which, with our imperfect devices, we can ever succeed in drawing.

And that light must travel in straight lines follows from whatever theory we adopt. If it consist—according to the old corpuscular theory—of minute particles radiated off from the luminous source, we can conceive of no other method of radiation than that they should be shot forth in straight lines from the source, and that they should continue their path until they meet something which will alter it. When they met such an object they would bound off and continue their course in a fresh direction, that is to say, they would be reflected. Or if the undulatory theory be preferred, we can perceive that those waves we can see for ourselves, liquid waves, produced say in water by any disturbance, such as a stone thrown into a pool, form circles spreading out from the point of disturbance, and that any selected point in any such wave moves straight away from the centre where the disturbance was set up. That it does so perceptibly we can see; that its path is absolutely and truly a straight line can only be shown by mathematical reasoning, the results of which, like much else in an elementary text-book like the present, must of necessity be accepted as true.

Let us then start from the basis that light from any luminous source diverges outwards in every direction from that source, and let us assume that the form this radiation takes is that of a succession of impulses, such as we term waves. Waves in water, remember, are visible only on the surface. As we see them, they are waves only in one plane. Waves of sound, however, and waves of light, must be remembered as proceeding not only over a flat surface, but, as it were, over an innumerable number of such surfaces; as started, not from the centre of a circle, but from the centre of a sphere.

Conceive a bell hung in the middle of a great hall and suddenly struck by the clapper. Instantly we have waves as spherical shells swelling out from the bell, and proceeding not only horizontally out in a surface parallel to the floor and ceiling, but in every direction, upwards and downwards, so that each wave has the form of a sphere, growing larger and larger, just as the circular waves which we see at the plane surface of the water grow larger and larger.

Again, let the bell be replaced by an electric lamp. Then we have similar spherical waves, but they are formed of vibrating particles of ether, instead of vibrating particles of air. As we stand looking at the lamp, the wave strikes against us, against the wall, the ceiling, the floor. Consider that portion of the whole wave that strikes the eye. Passing directly into the eye, it produces the sensation of vision. We *see* the electric lamp. Let us concentrate our thought on that part of the wave which is received by the eye, the ray which, emanating from the lamp, has struck the eye; and remember that the ray is not a material object, but a transmitted movement. The question arises, How is it that by the light emitted from the lamp we not only get a sensation of light, but that we can see the shape and appearance of the luminous body itself, and also the surrounding objects, the walls, the floor, the ceiling of the room?

A simple experiment will answer this question for us. If a sheet of white cardboard or paper be held near the flame of a candle, it does not show any image of the candle, as a looking-glass would, but if between the flame and the card we interpose another card, perforated by a large pin-hole, we see an image, or picture, of the

flame formed on the first card. Why is this? Let us make a diagram of the arrangement; it at once tells us why. We draw our candle, and our two screens, and then we draw a number of straight lines from different parts of the flame to the pin-hole, and produce them till they meet the card. If we could do this with a sufficient number of lines, it is evident we should obtain a picture of the flame, and as the lines all cross one another at

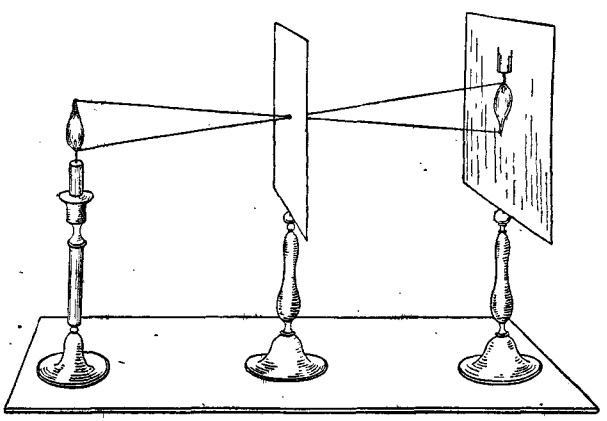

Fig. 1.

the pin-hole, the picture would be inverted. So with the lines of light. All that the pin-hole does is to cut off the superfluous rays. No rays except those from the top of the flame can reach the card where the point of the image-flame is. No rays except from the bottom of the flame can reach the base of the image. The smaller therefore the hole, the more sharply defined will be the image. If we enlarge the hole, we get a blurred image, but, as we are allowing more light to pass, a better

illuminated one, till, if we go on increasing its size, we get a round patch of light showing the shape of the hole, not the form of the flame.

A similar effect is produced if we prick a number of holes in the central card, close to the original hole. First we get other images of the flame. As the number of holes increases, the images overlap, till eventually they destroy one another, and we get an irregularly illuminated surface, showing shadows, since the solid part of the card still cuts off part of the light.

Now this rough experiment represents sufficiently for our purpose the action of the eye. We shall see later on that a lens acts just as a small hole does as regards the formation of an image, and we are therefore justified in representing the lens of the eye by our perforated screen, and the retina, on which that lens forms an image, by the card on which we threw an image of the candle-flame.

From this experiment we may derive a bit of evidence in favour of the undulatory theory of light. It is difficult to imagine that a number of material particles, however minute, could be driven through a small aperture in different directions without their interfering with each other, but we can observe for ourselves that waves in water, proceeding in different directions, will cross each other and pass onwards without change, and we can therefore imagine that waves of light may in like manner cross each other without any necessary alteration in direction.

But we see not only the source of light, but the various objects surrounding it. How is that? To answer this we must reply to another question, What becomes of

all the light that is emitted from a luminous source, in addition to the very small portion which strikes the eye of the observer? It of course falls on all surrounding bodies, and falling on them, rebounds, or is reflected. And as light thus reflected into the eye acts precisely as light proceeding directly from a luminous source, we are enabled to see objects by means of this reflected light, just as we can see objects which are luminous in themselves. This fact can be demonstrated by an extension of our experiment with the pin-hole and the candle-flame. If a small hole be pierced in the closed shutter of a darkened room, a complete picture of the outside scene will be formed on a sheet of white paper held up behind the hole, just as an image of the candle-flame was formed in the previous experiment. For the same reason the picture will be inverted, or upside down.[1]

In considering the manner in which we see objects by reflected light, it must be remembered that the light is not of necessity reflected directly to us from the source of light. It may be reflected many times, from many objects, before it reaches the eye. Notice the difference between direct sunlight and diffused daylight. In the case of the former we get brilliant illumination and dark shadows, because the light is all coming in one direction, being scarcely at all broken up or scattered. In ordinary diffused daylight the light originally derived

[1] This is the simplest form of *camera obscura*. The *camera obscura*, when constructed for purposes of exhibition, is made with a lens, which gives a brighter image. A very small amount of light passes through the little hole, and consequently only a dim image can be produced by it.

from the sun is reflected by clouds and by the innumerable minute particles which fill the air. It is broken up and scattered in every direction, and it penetrates into recesses, giving us more even but less brilliant illumination.

And the manner of reflection, too, has much to say to the result. If the light of a candle-flame falls on a mirror, we see a reflected image of the flame. If it falls on a sheet of white paper, we see a diffused brightness. If it falls on a strip of black velvet, we see no effect produced. Why this is so will be considered in the next chapter.

If an opaque object be interposed in the course of a pencil of luminous rays, it will evidently stop the passage of those rays which fall upon it, and the rest passing straight on will produce a shadow of the object, an unilluminated space corresponding in shape to the outline of the object.

It is evident, too, from common observation, that the nearer any object is to the source of light, the larger will be its shadow, and that the size of the shadow rapidly diminishes as the object is moved away from the light. It is on this principle that the entertainment known as "Magic Shadows" is arranged. The performers are behind a large illuminated screen, on which their shadows are visible to the spectators seated in front. When the performers are close to the screen, their shadows are of the natural size, but, as they approach the lamp by which the screen is illuminated, their shadows are enormously magnified, so as to produce the illusion of gigantic figures.

The calculation of the proportion of the size of the

shadow and the distance of the light is a very easy one. Suppose *A B C D* to represent a square of cardboard held up between a luminous point, *P*, and a wall. If we draw lines as in the diagram, from *P* to the corners of the card, and carry them on to the wall, these lines will follow the outline of the shadow, and the square, *E F G H*, will represent the shadow on the wall. It requires very little geometrical knowledge to enable us to see that the line *E F* bears the same proportion to *A B* that the line *P L*, the distance of the light from the wall, does to the line *P K*, the distance of the light from the card. Then the square of *E F* is to the square of *A B* as the square of *P L* to the square of *P K*. Now as the square of *E F* represents the area of the shadow, and the square of *A B* that of the card, this is only saying in mathematical language that the relative sizes of an object and its shadow vary precisely as the squares of the distances from the light.

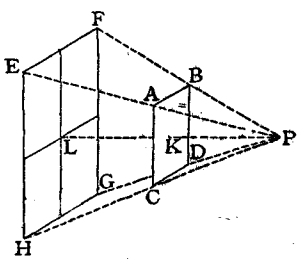

Fig. 2.

To take a concrete example. If the card be a foot off the light its shadow on a wall two feet from the light will cover four square feet, at three feet from the light nine square feet, at ten feet a hundred square feet, and so on. And note that the amount of light received by *A B C D* will, when it is removed, be spread over *E F G H*, and as the same reasoning applies, we may say that the illumination on any surface lessens as the square of the distance from the light increases; or, in the shape in which the statement is usually formulated, the intensity

of light is inversely proportional to the square of the distance.

It is important to realize the fact that this law is only true when the source of light is a mere point. Unless the light is so small, or the distance so great, that this may be taken as a fact, the law ceases to be true. This is evident from the construction of the diagram, which requires all the lines to meet at *P*. Again, the statement is true, not only of light, but of anything we can imagine radiating from *P*. If we imagine a shower of drops of water radiating in every direction from *P*, the

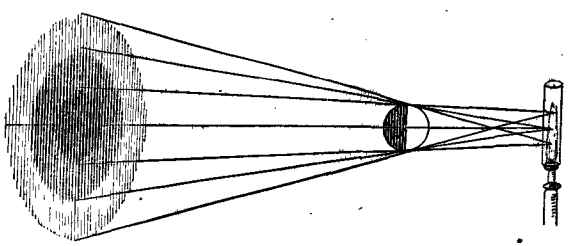

Fig. 3.

size of the space *E F G H* which would be kept dry by *A B C D* would vary as the square of the distance from *P*, and the amount of wetting which *E F G H* would get when *A B C D* was removed would vary inversely as the square of that distance.

Supposing *F* not to be a point, but, as of course it must always be in practice, a surface of some small extent, such as the flame of a lamp or candle, the shadow will not have sharp edges, but an ill-defined border, the precise limit of which it is not possible to decide. The reason of this is, that rays from the top and bottom of the flame which graze the edge of the object do not fall

upon the same place. Fig. 3 represents the shadow of a ball thrown on a wall by the flame of a lamp which has a large radiating surface. It is evident that rays from the base of the flame which pass over the top of the ball strike the wall much higher than rays from the top of the flame also passing over the top. So also with rays passing under the ball. The result is that the true shadow is surrounded by a lighter shadow where the background is illuminated by a part only of the flame. This lighter shadow is called the penumbra, and an eye placed within it will see part only of the

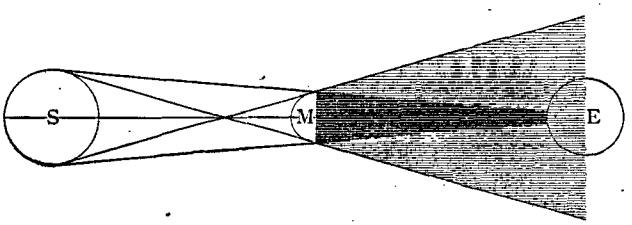


Fig. 4.

source of light. At the edge of the true shadow very little of the light will be seen, and at the edge of the penumbra nearly the whole.

The effect of the penumbra is very marked in eclipses. Fig. 4 shows what occurs in an eclipse of the sun, the sun being represented by *S*, the moon by *M*, and the earth by *E*.[1] The true shadow comes to an end behind the moon, but the penumbra extends considerably beyond it, so that the light of the sun is diminished some time

[1] It is hardly needful to remark that no attempt has been made in the diagram to indicate either the relative sizes or the relative distances of the sun, moon, and earth.

before the actual shadow touches the earth. In eclipses of the moon, the penumbra of the earth can be seen on the moon's disc long before the darker shadow reaches it.

If two lights of unequal brilliancy throw shadows of the same object, the stronger light will produce the darker shadow, and this fact has been utilized to provide a means of comparing, and so measuring, lights. The principle on which instruments for this purpose, known as photometers, are arranged, is that of removing the stronger light to such a distance that the two shadows

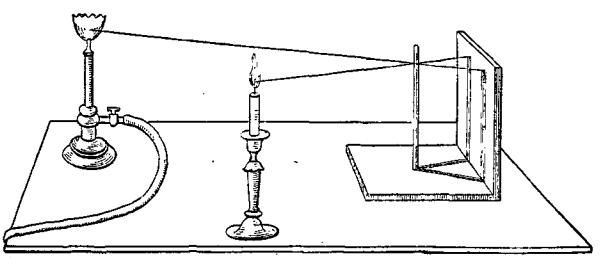

Fig. 5.

are equal, when a comparison of the distances of the lights from the screen enables their relative power to be stated with very great accuracy.

The best known photometer formed on this principle is that of Rumford shown in fig. 5. An upright rod, about the thickness of an ordinary lead pencil, is fixed in front of a screen, which in practice is usually translucent, so that the shadows can be seen from the back. The two lights to be compared, say a candle and a gas-flame, are so placed that the two shadows appear to be of equal depth. Measuring the distance of each light

from the screen, and squaring the amounts, we get figures representing the relative intensity of the lights.

Bunsen's photometer is even more ingenious. If a drop of oil be allowed to fall on a piece of paper, the greasy spot will be more transparent than the rest of the paper when it is held up to the light. But it will look darker than the rest when looked down upon. If it be placed half-way between two exactly similar lights, it becomes neither darker nor lighter, and so cannot be seen at all. In the instrument in question a disc of paper, with a translucent spot in the middle, is arranged

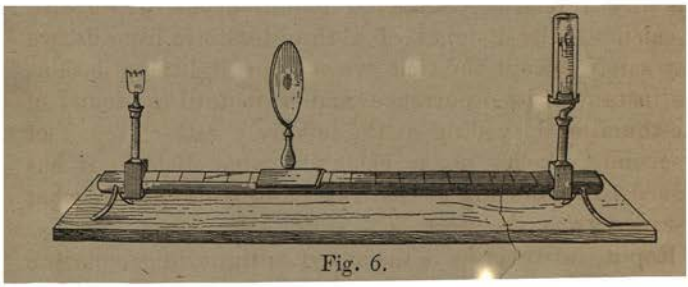

Fig. 6.

to slide along a scale, at either end of which are placed the lights to be tested. When it reaches the point where the two lights are equal, the spot disappears. Its position on the scale is then read off, and gives the relative intensity of the lights.

In practice it is not possible to obtain absolutely accurate results, unless both lights are of the same colour, as the eye cannot estimate precisely the strength of the shadows if there is any difference in tint. There is also a great want of a standard to which all lights can be referred. In England a certain sort of candle is used,

in France an oil lamp, but it is never possible to be quite certain of the absolute identity of the light given by either means. Many proposals have been made, but a standard of light which can be trusted to give results of scientific accuracy has yet to be discovered.

The velocity with which light travels is so great, that it was at one time believed to be transmitted instantaneously through space. This, however, is very far from being the case, and the speed at which it travels has been ascertained, by several perfectly distinct methods, to be about 186,000 miles a second. For all terrestrial purposes, this may indeed be considered instantaneous. If we wish to calculate the distance of a thunderstorm from us, we may safely accept the time we see the lightning flash as the instant of its occurrence, and wait until the sound of the thunder, travelling at the leisurely rate of 1000 feet a second, reaches us, to calculate what distance it has passed over, moving at that rate, and consequently what distance away the storm is.

Rapid, however as is the speed of light, in comparison with earthly measurement, it seems less difficult of realization when we think of it in connection with the distances of space, the distances which separate us from the heavenly bodies surrounding us. The light which reaches us even from our own sun has been more than eight minutes on the road, while that which comes from a distant star has probably started on its journey thousands of years ago. Consider what this means. The star we are looking at is not the star which is now, but the star which existed when Cæsar landed in Britain, or when the first Pharaoh reigned in Egypt. Could we conceive ourselves possessed of instruments of power such as to

enable us to behold the surfaces of those far-off orbs, we should be spectators of the events of long past ages. Or to let imagination run riot yet a little more freely, let us fancy ourselves to be transported instantaneously to a distant fixed star, and endowed with vision such as to enable us to see what was going on upon this earth. We might, as some ingenious speculator has suggested, according to the point of view selected, contemplate the events of a few years ago, or a few centuries, or even of the dim ages before the making of man, when the "monstrous eft" was the lord of creation.

## CHAPTER II.

### REFLECTION.

Angle of Incidence equals Angle of Reflection.—Mirrors.—Multiple Reflections.—The Kaleidoscope.—"Pepper's Ghost."—Curved Mirrors.

IF any object strike any surface it will tend to fly off at the same angle as that it made in striking the surface. The angle of reflection is equal to the angle of incidence and in the same plane with it. This is equally true of a billiard ball striking the cushion of a billiard table, or of a ray of light striking the surface of a mirror. For convenience sake we generally measure this angle, not from the surface itself, but from the normal, or perpendicular to that surface. Thus, if *E A* is the direction of the moving body, *E A D* is called the angle of incidence, and *D A F* that of reflection. That the angle of reflection is equal to the angle of incidence may be demonstrated approximately by several simple experiments. That it is true, as far as human senses can appreciate it, may be taken as proved by the fact that certain astronomical instruments depend for their correct working upon its absolute truth, and that in none of them, though they

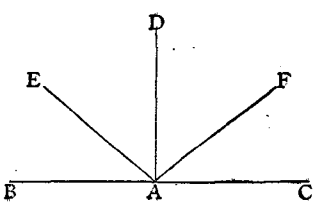

Fig. 7.

are graduated with the minutest accuracy, has the slightest deviation ever been detected.[1]

Naturally the simplest form of reflection is that from a smooth surface, such as the surface of a mirror. Let us consider the case of a small point of light, such as a star, reflected in a mirror. The rays of light from the star fall on the mirror, and are thence reflected in the same plane to the eye, so that we see in the mirror a perfect

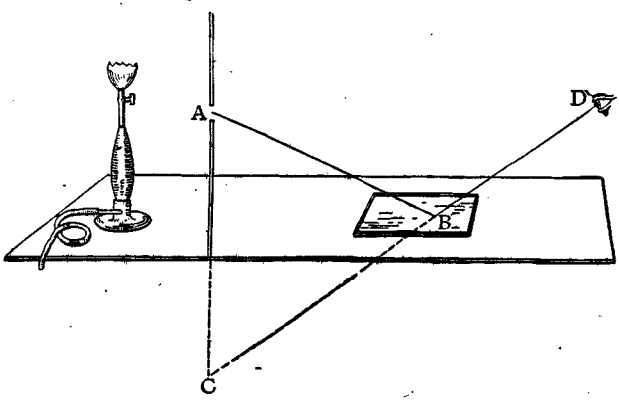


Fig. 8.

image of the star, just as if the eye had looked at the star. Let us repeat the experiment with an artificial star. Lay a looking-glass on the table, and at a convenient distance arrange a screen with a small hole, having behind it a

[1] "The best experimental proof of the truth of this statement is deduced from the use of a reflecting surface of mercury in observations with the mural circle. The graduation of such an instrument is the most perfect that human skill can accomplish, and no one has ever been able to find by it the slightest exception to the preceding statement."—Prof. Tait, Art. "Light" in *Encyclopædia Britannica.*

bright lamp. Thus in our diagram (fig. 8) *A B* represents the path of the light, *B D* its path after reflection. The eye will see it as if it came from a point as far behind *B* as *A* is distant from *B*, that is, a point *C* directly under *A*. For note that the eye has absolutely no power whatever of judging of the original source of reflected light. It only feels the ray strike it in a definite direction, that of the last reflection, and it places the point of origin somewhere along that line. From comparison of position among surrounding objects it also has a certain power of estimating the place whence a ray started, and the consequent distance of that place, but in the case of reflections it is apt to be woefully deceived, as we may realize whenever we look at a mirror.

Obviously if the above statement is correct for a point of light, it will be so for a larger body, which may be considered as an assemblage of such points. Remove the screen, and we get an image of the flame as far beyond *B* as the flame is distant from *B*, or the actual distance of the flame from the eye, measured along the path *A B D*, by which the light has travelled.

It is to be remembered that rays from the flame fall on every point of the mirror, but only those which fall on the mirror at such an angle as to be reflected into the eye can be perceived by it. This is illustrated in fig. 9, in which are shown the rays which fall from the flame *L* on the face of the mirror *A B*, at such an angle as to be reflected into *E*. From the course of these rays it is seen that a mirror gives images of objects in their natural position, that is, not inverted, as we of course know to be the case.

This gives us a rule for reflections from all plane

mirrors, that is, from all polished surfaces which are smooth enough to reflect light quite evenly and regularly, without breaking it up or scattering it. The eye can see reflected in a mirror all objects which are in such a position that lines making the same angle with the surface can be drawn from any point in the mirror to the object and the eye. If that is the case, a ray can pass from the object, strike the mirror, bound off at the same

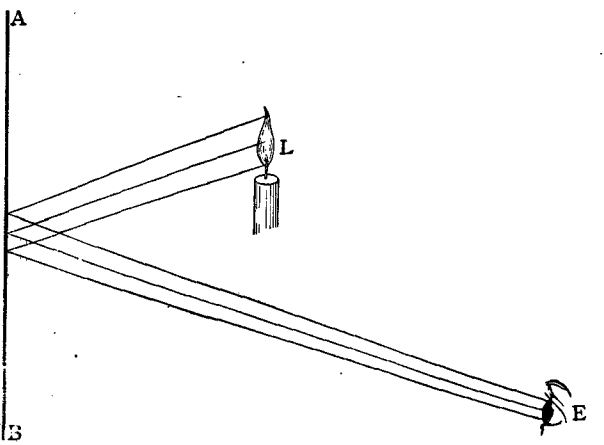


Fig. 9.

angle, and enter the eye. If it is not, the ray from the object may strike the mirror, but it will not enter the eye until the eye has been moved into a position to receive it. The application of this simple reasoning shows at once how it is that we can see objects in a looking-glass as if they were beyond and behind the frame.

Remove the mirror and substitute a sheet of white

paper. The light still falls at the same angle, but we get no reflection, only a white glare. Why? Because the surface of the paper is rough. It consists of minute hills and dales, against the sides of which the light strikes, and from which, therefore, it is reflected at all sorts of angles. Our symmetrical image is therefore broken up and mixed together, and we get no distinct form, only the mixed and scattered light. If the beam be received on a dead black surface, such as that of black velvet, only a small proportion of the light will be reflected. The rest will be absorbed; not indeed destroyed, but degraded, so that the radiation no longer is sensible to our eyes as light.

It is to be remembered that light can only affect the eye when it enters directly into it, either from some luminous source, or reflected from some object. Light, however brilliant, passing before the eye is not perceived by it. We can, indeed, perceive the passage of a beam of light through the air, but that is because in its passage it lights up the numerous floating particles in the air, and by them it is reflected to the eye. If the beam is caused to pass across a space cleared of such particles its path cannot be traced. Professor Tyndall has often shown, at the Royal Institution, a beam from the electric lamp traversing a large glass globe in which the floating particles had been allowed to settle. On either side of the globe the beam was visible enough, but within the globe itself the beam could not be seen.

But we need no special arrangements to see this experiment performed for us on the most stupendous scale. On any clear moonless night the whole universe appears dark to us except for the brightness of the stars.

Yet the sunlight is poured out upon the earth and surrounds it on all sides. We are merely in the shadow of the earth, and the sun's direct rays are cut off from us. We therefore are sensible of none of them, except of the few which are reflected to us from those of the heavenly bodies which obtain their light from the sun. Thus we are compelled to admit the seeming paradox, that light, by which we see all surrounding nature, is itself invisible.

The passage of the beam from an electric lantern across a darkened room will but very slightly dispel the darkness, but if the beam falls on a white sheet, at once the dispersed light fills the room, and objects are distinctly seen. Or let the beam be directed into an empty glass vessel, or a vessel of clear water, and still the room is dark. But if the vessel be filled with smoke, or the water be made turbid by the addition of a little gum dissolved in spirit, or even by pouring into it a little milk, then at once the vessel becomes luminous, radiating light throughout the room.

We have considered the different effects of reflection from three classes of surfaces. The brilliantly polished surface reflects a very large proportion of the incident light. The dull velvet surface reflects a very small proportion. The surface intermediate between the two, smooth but unpolished, reflects a varying amount, according to its texture, while dispersing the light in all directions. There is, as would naturally be expected, an infinite amount of variation in this respect, corresponding with the infinite variety of surfaces. The best reflector is perfectly polished metal. The next best is glass. In our ordinary mirrors we have both such surfaces, the front surface of the glass, and the surface of the film of

metal on the back of the glass. The latter is far the better reflector, since it allows no light to pass through it, but turns it all back. The glass reflects part and transmits part. If we look at a rather oblique angle at the image of a flame in an ordinary mirror we shall see two images, one from the front surface, the other from the back. *A* is a luminous point, the rays from which strike the mirror *B C* at *b*. Some are reflected at once, and give an image apparently situated at *a*. Others pass through the glass, and are reflected from the silver surface at $b_1$, giving an image apparently at $a_1$.

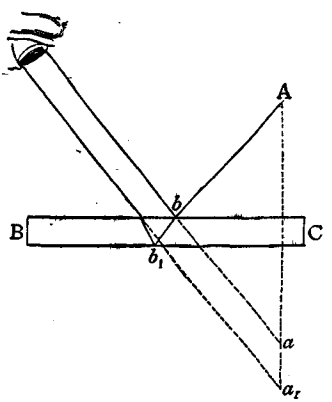

Fig. 10.

Light may of course be reflected more than once. The reader must frequently have observed the effect produced by two mirrors opposite one another. The images produced in the first are reproduced in the second, these again in the first, and so on till we get a series of these multiple reflections, each one a little fainter than its predecessor from absorption of part of the light, and probably from the colour given by the repeated passage through the thickness of the glass, till the smallest, and apparently the most distant, of the numerous images appears to be lost in shadow. In this case the number of images is theoretically infinite.

The experiment can be reproduced on a small scale by setting up two pieces of looking-glass with a candle

between them. On looking at one mirror from the edge of the other a number of images will be seen.

If, instead of using two mirrors facing one another, we use two set at an angle, the effects are apparently different, though they are in reality due to the same cause, multiple reflection.

If two small mirrors are set up edgewise on the table in the position shown in the diagram, and any small object, such as a flower or leaf, be placed in the angle between them, it will of course be reflected in each mirror; each reflection will be again reflected, and the result will be that there will be a circle of images arranged symmetrically around the line of intersection of the mirrors, the original object being inclosed in the circle. If any irregular marks be scribbled on a piece of paper, and the mirrors be stood up on the paper, the repetition of the marks will produce a symmetrical pattern, or a like effect will be produced by scattering some coloured beads on the paper.

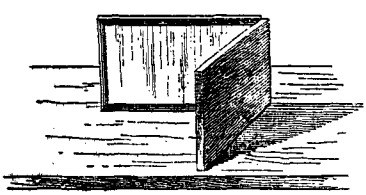

Fig. 11.

According to the smallness of the angle between the mirrors, so will be the number of reflections. If the mirrors be set at a right angle, three reflections and the original only can be seen, if at angle of 60°, the original object and five images. An angle of 90°, or a right angle, is of course the fourth of the whole circumference of 360°, an angle of 60° is the sixth, so the relation of the number of images to the angle is easily seen. Divide 360 by the number of degrees at which

the mirrors are inclined to each other, and we shall have the number of images, counting the object itself as one. Fig. 12 illustrates this. The actual figure is what we see in the space $A$. In $B$ $B_1$ we get a first reflection; in $C$ and $C_1$ a second; in $D$ the third reflections on each side coalesce. As in each reflection light is lost, the successive images are each slightly dimmer than the one before it.

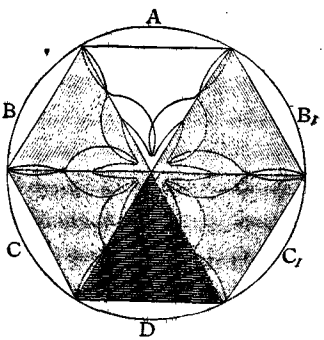

Fig. 12.

The manner in which the images are formed is shown diagrammatically in fig. 13. $A$ is a real object, $O$ the point of sight, $M$ $M_1$ are two mirrors inclined at an angle of 90°. $A$ is reflected in $M$ and $M_1$, and we get the images $A_1$ $A_2$. The reflection of $A$ in $M$ is also reflected in $M_1$, and thus we get a third image, which looks as if it were situated at $A_3$. The reflection of $A$ in $M_1$ is also repeated in $M$, but from the position of the point of view it cannot be seen. If the point of sight moves over from $O$ to the other side of $A$, the third image will then be the result of a first reflection in $M_1$ repeated in $M$.

In the above arrangement we have constructed a simple form of kaleidoscope. In this well-known instrument two mirrors are arranged in a tube, at an angle of 60° (sometimes a third mirror, completing the triangle, is employed). An eye-piece is fitted at one end of the tube, and the other is fitted with a cap, in which a few bits of

coloured glass are held between two flat pieces of clear glass.

It has been noticed that the eye is unable to tell the actual source of a reflected ray of light, seeing it just as if it started from a point in the line of the last reflection. This fact has been utilized in the ingenious illusion first introduced to the public under the name of "Pepper's Ghost,"[1] and since employed in various modifications for

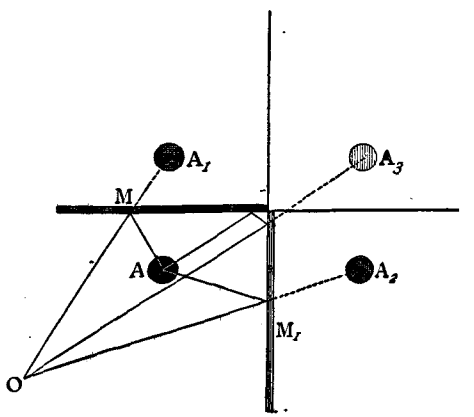


Fig. 13.

theatrical purposes. In this device the "ghost" is viewed by reflection from the surface of a sheet of plate glass, while any actual objects behind the sheet of glass are of course visible too. The eye views the reflected object as if it were behind the glass, and consequently among the objects actually behind it. The precise arrangement is shown in the diagram (fig. 14). *F G* is the

[1] The illusion was really invented by Henry Dirckes; it was brought out at the Polytechnic by Pepper.

floor of the stage, in front of which is a well, invisible to the spectators, and in this well is placed the object *A B* which is to be seen by reflection. *A B* is reflected in the sheet of plate glass *E F*, and therefore appears to a spectator at *O* to be situated at *C D*. The object is brightly illuminated, while the floor and walls of the well are of a dead black, so as not to reflect light. Fairly distinct "Pepper's ghosts" may be observed by looking out of a brightly lighted room into a rather dark street. The reflections of the fire or the lamp in the window, looked at at the right angle, then appear to be out in the road. Or if at night, in a railway carriage, we look at

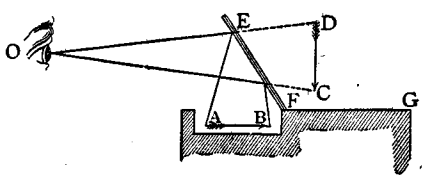


Fig. 14.

the reflections of the interior of the carriage, they appear to be mixed up with the landscape outside, or with the people in the railway station, if the comparative amounts of light inside and outside the carriage are suitable.

Professor Weinhold [1] describes an excellent way of demonstrating this illusion. If a sheet of glass be supported as shown in fig. 15, having on one side of it a bottle or tumbler of water, and on the other a lighted candle, the eye, looking direct at the water-bottle through the glass, will see the reflection of the candle at the same place, and the candle will appear to be burning under

[1] *Experimental Physics*, p. 436.

the water. If the room be rather dark, and if the candle itself be hidden behind a book or a board, the illusion is complete.

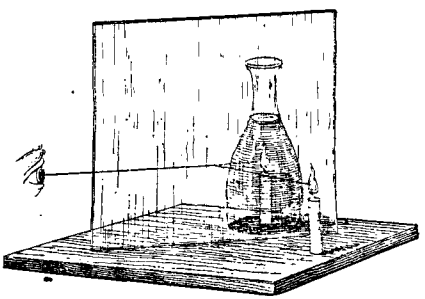

Fig. 15.

On the same principle a very simple and ingenious arrangement has been devised for copying sketches. If a piece of plain glass be supported as shown in the diagram, and the picture to be copied be laid by the

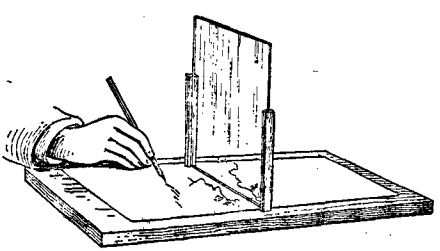

Fig. 16.

side of it, on looking through the glass at a sheet of white paper on the other side a reflection of the picture will be seen apparently projected on the white paper. The lines of the picture can then be traced over by a

pencil, which of course is perfectly visible through the glass. It is even sufficient to hold the glass with one hand, provided it be kept steady, and not allowed to shift its position. The picture, it should be noted, will be reversed, right for left, just as an image is in a looking-glass.

Hitherto we have considered only the case of reflections from a flat or *plane* mirror. When the surfaces on which the light falls are curved, we have a different set of conditions, and so we may expect different results. These results are however to be explained by the same laws as govern reflections from plane mirrors. The curve of the surface must obviously be turned either towards or away from the source of light, that is to say, the surface must be either convex or concave. We have, therefore, two classes of curved mirrors to deal with, convex and concave. And if they are to give symmetrical images, they must be truly round, or spherical.

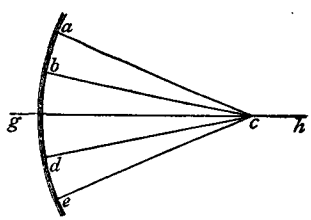

Fig. 17.

Fig. 17 is a section of a concave spherical mirror, *c* being the centre from which the curve is struck. We may regard it as a portion of a large spherical shell, of which *c* is the centre. Now the first thing to notice is, that if we place a light at *c* the rays from it will all be reflected back directly to *c*, since all lines drawn from the centre of a circle to the circumference must be perpendicular to the circumference, and as the angle of reflection is equal to the angle of incidence, the ray must return along the line of the perpendicular. The line *g h*,

which passes through the centre of curvature and the centre of the mirror itself, is called the axis. If now we move the light along the axis in a direction away from the mirror, to any point $f$, fig. 18, we shall find that the rays from $f$ are all reflected to a point $f_1$, between the centre $c$ and the mirror. The further away we take $f$, the nearer will $f_1$ approach the mirror, the angle of incidence from $f$ being always equal to the angle of reflection to $f_1$.

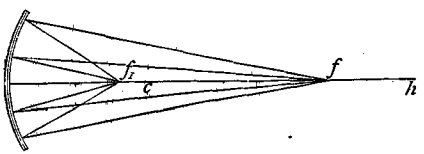

Fig. 18.

When we have removed $f$ to such a distance that we can no longer perceive any inclination between the lines proceeding from it, and they are therefore sensibly parallel, $f_1$ will have reached a position exactly half way between the centre $c$ and the mirror, as in fig. 17. If, therefore, we receive the light of the sun (which comes from such a distance that the rays are parallel) full on a concave mirror, we shall find that all the rays are reflected to a point near the mirror, midway between the centre of curvature and the centre of the mirror. A bright spot of light will be formed on a white piece of paper there, or if any inflammable material be placed there it will be set on fire. For this reason the point is called the *focus*, or more properly the *principal focus*, of the

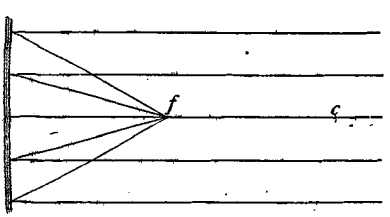

Fig. 19.

mirror, *focus* being a Latin word signifying *hearth.* It has been proposed to use large mirrors for concentrating the sun's heat in hot countries, so as to boil water for raising steam, and this has indeed been done experimentally on a sufficiently large scale to prove its possibility.

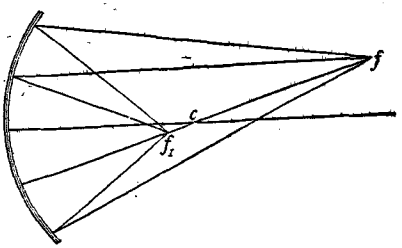

Fig. 20.

A similar train of reasoning shows us that if the light is moved nearer the mirror the rays will be concentrated at a point which becomes more and more distant until the rays are parallel, when the light will be at the principal focus. Lighthouse reflectors are made

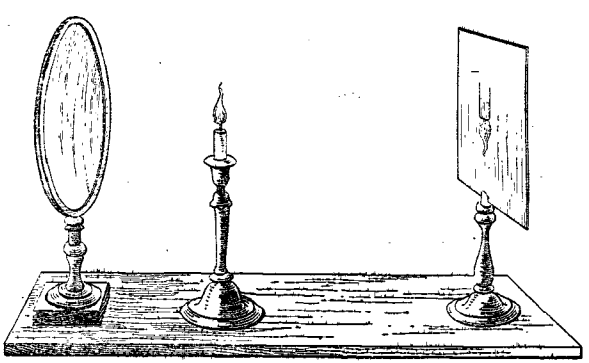
Fig. 21.

on this principle, the light being set in the focus of a curved mirror.

If then we place a light at $f$ it will be focussed at $f_1$,

and if we place the light at $f_1$ it will be focussed at $f$. Any two points thus related are termed conjugate foci, and every point along the axis of a mirror has a corresponding point on the other side of the centre of curvature, which is its conjugate focus.

If the luminous point be not on the axis as $f$ in fig. 20, a corresponding point $f_1$ can still be found on the opposite side of the axis, and $f$ and $f_1$ will still form conjugate foci. It should be noted that a line from $f$ can always

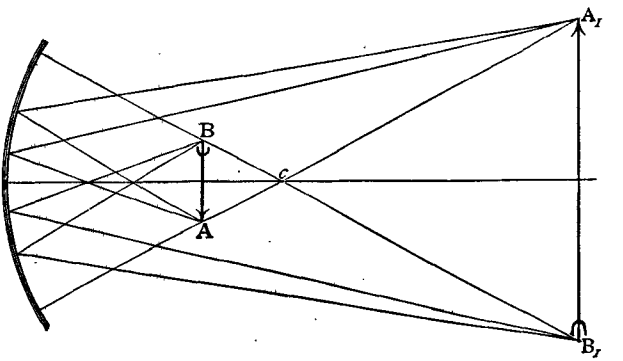


Fig. 22.

be drawn through $c$ to the surface of the mirror, and that the geometrical construction will be the same if this line be treated as an axis of the mirror, the surface of the mirror being, if necessary, supposed to be enlarged so that the line may fall upon it. The conjugate focus will always be on this line.

Since then a concave mirror will focus the rays from any point of an object to a corresponding position at the conjugate focus of that point, it ought, by thus treating

all the rays from every point of the object, to form an image of it which can be received on a screen. And this is the fact. If a candle be placed in the position relative to a concave mirror represented by $f_1$ in fig. 21, and a screen at $f$, we shall get on the screen an enlarged and an inverted image of the candle-flame. Plotting it out in a diagram we see how this image is formed. It

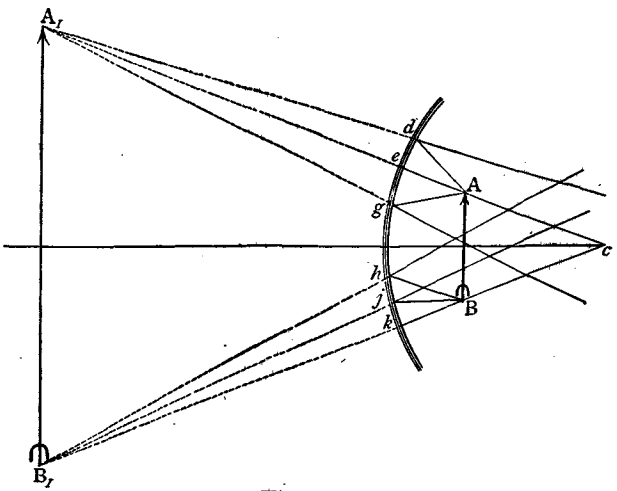


Fig. 23.

is only necessary to give the rays from the top and bottom of the object, so as to avoid confusion. $A\,B$, fig. 22, represents the object; then the rays from $A$ will all be focussed at $A_1$ and the rays from $B$ at $B_1$. $A$ will be on the opposite side of the axis to $A$, and $B$ to $B$. Also $A_1$ and $B_1$ will be farther away from the axis than $A$ and $B$. Therefore the image will be inverted and magnified. If we consider $A_1\,B_1$ to represent the object,

and *A B* the image, the image will then be smaller than the original, but still inverted.

It is important to note that these images are *real*. They can be received on a screen, or they can be viewed by the eye from behind. In this respect they are quite different from the images formed by plane mirrors. These latter are called *virtual* images, though indeed it would be better if some other name could be found for them since they have no real existence. A virtual image is only the imaginary position from which reflected rays appear to originate, and to which they are therefore referred by the eye.

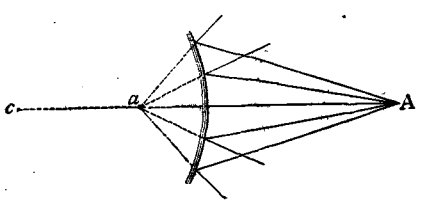

Fig. 24.

A concave mirror can however form a virtual image. If the object is placed nearer the mirror than the focus, as at *A B*, fig. 23, the rays falling from it on the mirror do not converge at all, they are scattered, and never come to a focus. The rays from *A* falling on the mirror at *d, e, g*, will be reflected in such directions that they all appear to start from $A_1$, and the eye assumes that they do so. Similarly the rays from *B*, which strike the mirror at *h, j, k*, appear to start from $B_1$. The result is the formation of a virtual image, $A_1 B_1$. This image is erect and enlarged. It is seen by an eye in front as if it were behind the mirror, as in an ordinary looking-glass.

The rays falling on convex mirrors can never be converged. If, as in fig. 24, they proceed from a point *A*,

they will be rendered more divergent, and will appear to the eye to diverge from the point *a* behind the mirror, and if any object is placed at *A* an erect virtual image will be the result.

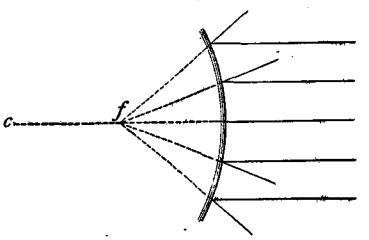


Fig. 25.

Rays parallel to the axis which fall on a convex mirror are radiated as though from a point *f*, half way between the centre of curvature and the mirror, as shown in fig. 25.

## CHAPTER III.

### REFRACTION.

Nature of refraction.—Refracted images in water.—Refraction by a prism.—Total reflection.—Luminous Fountains.—The mirage.

WHEN light falls on a transparent surface we have seen that part of it is reflected. We know of common observation that part of it passes through. We should expect that the proportion of the amount reflected and the amount transmitted would vary with the angle of incidence, and this is so. The proportion will also vary with the nature of the substance. Take water for instance. If the light falls full on the surface, that is to say at a right angle, only two per cent. (more accurately 18 per 1000) are reflected, the remainder passing through. If the angle of incidence, the angle which the ray of light makes with the perpendicular, be 40°, 22 per 1000 will be reflected; at 89½°, half a degree less than a right angle, or when it just grazes the surface, 721 out of 1000 will be reflected, but even then a quarter will enter the water.[1]

The question we have now to consider is, What happens to the transmitted rays? Do they continue their course unaffected? From ordinary experience we might at first say they do. When we look through a half-opened

[1] Tyndall on Light.

glass window, we seem to see objects just in the same straight line, whether we look at them through the glass or through the part of the window which is open. As a matter of fact we see them in nearly the same line, but not quite. The course of light passing from one medium to another is at once changed. If it passes from a rarer medium to a denser (as from air into glass) its path is bent *towards* a line perpendicular to the surface at the point of incidence. If it passes from a denser medium to a rarer, as from glass to air, it is bent *from* that perpendicular.

The diagram, fig. 26, shows the actual course followed by a ray of light passing through a plate of glass. As it strikes the glass at *a*, it will be bent *towards* the perpendicular. On emerging at $a_1$ it will be bent *from* the perpendicular to the same extent, and will pursue a course parallel to, but not in a line with, its former path. Or if we regard the light as coming from an object at *b*, it will be bent into the direction *a O*, and an eye at *O* will receive an impression of light coming in the line $b_1$ *a O*, and will see the object at *b* as if it was at $b_1$. The amount of the deviation of the ray, as the diagram shows, depends on the thickness of the glass. With ordinary window glass it is too slight to be perceptible, and so we never notice it. It may, however, readily be shown to exist. Take a thickish piece of plate glass, and lay it on a piece of ruled paper, and it will be seen, if we look at them at an angle, that the lines as viewed through the glass appear not to be quite con-

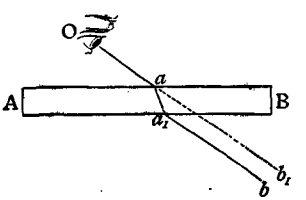

Fig. 26.

tinuous with the parts outside the glass. They have the appearance of being shifted a little away from the eye, the amount of the shifting becoming greater as the angle at which the lines are looked at is increased. If they are viewed from a point directly above, that is, at right angles, no alteration is perceptible. Rays impinging at a right angle on a surface suffer no refraction. If they are seen at a considerable angle, the difference is marked. The effect may be increased by placing several pieces of glass one atop of the other.

The familiar phenomenon of the apparent bending of

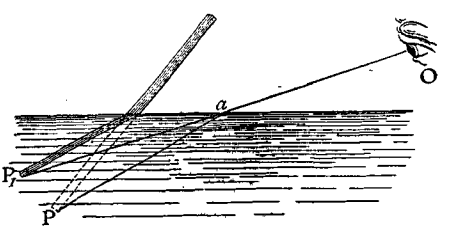


Fig. 27.

a stick partly immersed in water is explained by a precisely similar course of reasoning. The ray which really comes from the end of the stick $P$ is bent as it passes out at $a$ from the water into the air and pursues the course $a\,O$. The eye at $O$ assumes that light reaching it along $a\,O$ must come from a point along that line, so it sees the end of the stick at $P_1$. And so with all the other points along the length of the stick immersed in water. The ultimate result of this is that the stick appears to be bent when it enters the water.

Another well-known experiment is to place a coin in a basin or cup, and to set the cup in such a position that

the coin just cannot be seen. If water be poured into the cup, the coin becomes visible, for the rays which before proceeded in a straight line from it to the eye, and were interrupted by the rim of the cup, are now bent round as they leave the water, and so pass over the rim to the eye. In the diagram, fig. 28, *a* shows the actual position of the coin, *f* the position to which it is apparently lifted by refraction. We are reminded by such experiments as these, that though we say generally that light travels in straight lines, it is only when it is passing through a uniform medium. Whenever it passes from one

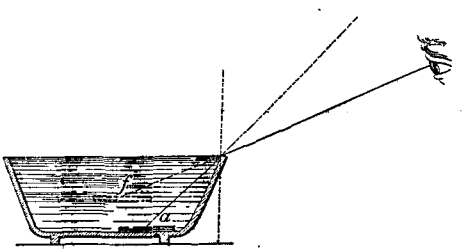

Fig. 28.

medium to another it is liable to refraction. Light is refracted when it enters the atmosphere surrounding our earth, and so we see the sun after it has actually set, that is, after it has reached such a position that the horizon is between us and it.

There is one special case of refraction which requires particular attention. We have seen what happened to a ray passing through a plate of glass with parallel sides. It was refracted at its entrance, and refracted again at its exit in such manner that its path after leaving was parallel to its original path. Supposing the sides not to

be parallel, but inclined to one another. What will be the effect on a ray passing through a wedge-shaped piece of glass, or as it is usually called, a prism? If a ray of light from $a$ strike at $b$ on the side $A\,B$ of such a prism, $A\,B\,C$, it will be refracted to $b_1$; here it meets at an angle the side $A\,C$, and will be again refracted, as it leaves the glass (passing from a denser to a rarer medium), to $a_1$. The path of the ray will therefore be $a\,b\,b_1\,a_1$, that is to say, it will be bent towards the base of the prism.

We shall see hereafter that the prism is perhaps the most important optical instrument we possess. All we have to remember for the moment is its power of bending the ray twice in the same direction, so that its path after leaving the second surface may be at a very considerable angle to its path before it met the first surface.

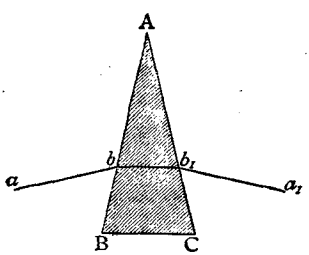

Fig. 29.

Prisms may vary greatly in shape and material; they may be of glass or other transparent substance, or of liquid contained in a wedge-shaped vessel with transparent sides. The angle through which an incident ray is deviated will vary with the material of the prism and the inclination of its sides to each other.

Supposing $O$ in the diagram, fig. 30, to be an object under the surface of water, $A\,B$ being the line of the surface, $O$ is reflecting rays of light in all directions. As these rays pass up into the air they are refracted. $O\,a$ is refracted to $a_1$, $O\,b$ to $b_1$; the angle of refraction increases as the incidence on the surface of the water

becomes more oblique. *O c* is refracted to $c_1$; it just grazes the surface. What will happen to *O d*? It cannot get out of the water. It is bent back into the water, and we have instead of refraction, reflection—reflection from the surface of the air, at all events from the surface where the air and water meet. And there is this remarkable characteristic about it. The reflection is *total*. All the light is reflected. When light in air falls on water this never happens, however great the angle of incidence. When light in water falls on air, it always happens, if the incidence is as much as 50°. To speak more generally, total reflection may occur whenever light passes from a denser medium towards a rarer one, at a certain angle.

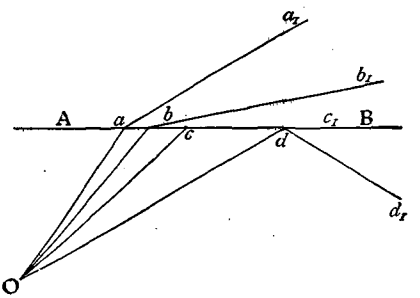

Fig. 30.

Now, if all the light from an object is reflected, it follows that the image must be as brilliant as the object, since we receive the same amount of light whether we look direct at the object or at the object after reflection. The same amount of light reaches the eye, though in the second case by a rather longer path. This fact is easily illustrated. If a bright coin be placed in a glass tumbler partly filled with water, the reflection of the coin is seen apparently floating at the surface of the water when the glass is held above the eye and slightly inclined so that the surface of the water can be viewed from underneath. This should be done near a bright light, so that the coin

itself may be well illuminated. The precise position will easily be found by trial. It will be noticed that the reflected image seems quite as bright as the object, brighter than if the coin had been reflected in a looking-glass.

The same effect may be more strikingly observed in an aquarium when a fish is swimming near the surface of the water; the spectator, looking at him from below, can always, if the water be smooth, see another fish, swimming just above him. The reflection is so bright that there is no perceptible difference between it and the fish which cast it.

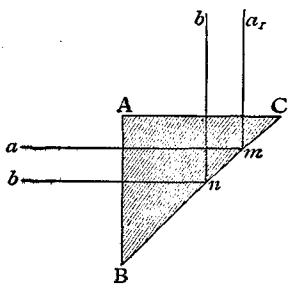

Fig. 31.

It is to the total reflections from their internal surfaces that glass lustres owe much of their brilliancy. If one of the prisms be placed so as to allow light to fall more or less directly upon one of its faces, while it is held horizontally in the hand, it will be noticed that the inside of the opposite face, the one that is visible through the glass, shines like polished silver —far more brilliantly than the outer faces. This is because the light, passing into the glass without hindrance, is reflected entirely from its inner surface. This may be a little clearer if we consider the following diagram of a totally reflecting prism, a device frequently used in optical instruments, when it is important to reflect light without loss. *A B C* is such a prism, the angles at *B* and *C* being 45°, or half a right angle. Rays of light *a* and *b* falling perpendicularly on the face *A B* of the prism,

suffer but little reflection, and no refraction, so that they pass on almost unaffected to the face *B C*. Here, instead of passing out again into the air, as would naturally be expected, they are totally reflected, and pass out through the face *A C*. Meeting this at a right angle they can pass through again without loss.

By dint of repeated internal reflections light can be carried along the inside of a solid glass rod, and it has been proposed to use this device to guide light for dental and surgical purposes into the mouth and other parts of the body. This is an application on a small scale of the same principle which has been so successfully applied to the illumination of fountains for popular entertainments. The light from a powerful electric lamp is reflected into the base of the fountain jet, and the light thus received into the jet is reflected to and fro within it, being for the most part unable to escape, though a certain portion does escape, and renders the jet visible. The effect is heightened by interposing sheets of coloured glass between the lamp and the water, so that the light is coloured before it enters the jet.

We are now in a position to understand the explanation which has been given of the wonderful phenomenon of the mirage, by which in hot flat countries the appearance is produced of lakes of water, often with trees and buildings reflected in them. The sun's rays, beating down on the desert sand, heat the surface strongly. This heat is given off to the air close to the ground, the heated air expands, becoming less dense, and rises, and eventually we get a series of layers or strata of air, of which the hottest and the least dense is some distance above the ground, the strata nearest the ground being the

densest, as least heated. These strata are indicated by the lines in fig. 32. Consider the course of a ray from a point $M$ near the top of the tree. As it passes at $a$ into a slightly denser stratum of air, it will be refracted from the vertical, at $d$ it will be again refracted, until it has been bent to such an angle that at $A$ it will strike a surface at the angle of total reflection, and will then be turned upwards. It will be bent more and more as it passes on through $d^1$ and $a^1$, reaching in succession strata of less

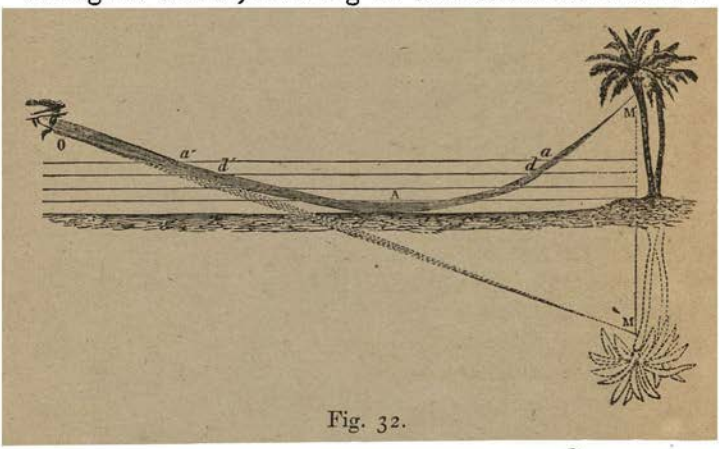


Fig. 32.

and less density, till at last it reaches the eye at $O$, in a direction as though it had started from $M^1$. All the rays starting from different parts of the tree will be thus acted on, and an inverted image of the tree will be the result.

In the same way light from the sky will be reflected from the strata of air between the tree and the spectator, and this reflecting surface will give the effect of water. The spectator may therefore see the tree by rays proceeding directly from it, the reflecting surface which

simulates water, and the image of the tree which will appear to be reflected in the water. If there are no actual trees or buildings, the mirage will simply produce the illusion of a lake of water alone. At sea similar effects are seen, the inverted images of ships having been observed apparently in the sky. These effects are certainly due to strata (more or less defined) of air of different densities, serving as refracting media.

## CHAPTER IV.

### COLOUR AND THE SPECTRUM.

Decomposition of White Light.—The Prismatic Colours.—Absorption.—Recomposition of White Light.—Colour Discs.—"Primary" Colours.—Colour Combinations.—Complementary Colours.—Colour Blindness.—Accidental Colours.—Effects of Contrast.—Coloured Shadows.

WE have hitherto dealt with light as if it were homogeneous, as if it could be reflected or refracted without any other change than a change in direction or a change in intensity, produced by scattering or by absorption. That light of a certain quality can be thus dealt with is perfectly true, but the supposition would not be entirely true of ordinary white light. Ordinary white light is, as is well known, made up of an infinite variety of coloured lights. We have now to consider what this statement means.

The decomposition of white light, its resolution into its components, is easily effected. If a bright light from a small source, such as a small hole in a window-shutter through which the sunlight can pass, or in a screen with a brilliant light behind it, be looked at through a prism of moderate angle, not only will the position of the spot be displaced (as described on page 44), but in place of the bright spot of light an elongated image of the spot, gorgeously coloured, will be seen. If the rays are

allowed to fall upon a screen we shall see on the screen a coloured strip, showing the colours familiar to us as those of the rainbow. We shall see, if the prism is set with its point down, as shown in the diagram, that the lowest colour is red, that this gradually shades off through orange into yellow, which changes by insensible gradations into green, the green gradually altering into blue, and the blue darkening, finally disappearing into shades which have been termed indigo and violet. The coloured image thus produced is known as a *spectrum*.

By looking at the course of the rays, as they mark out

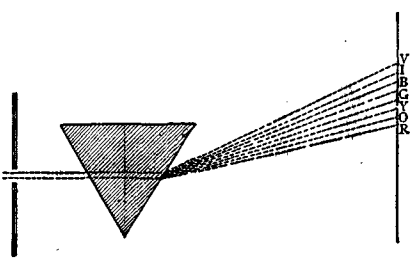


Fig. 33.

their path in the dust-laden air, or by consideration of the diagram, we can understand what happens. We see that all the rays are bent, as we expect them to be, by refraction in passing through the prism, but we see that some are bent more than others. The red are bent the least, the blue and violet the most. We may at once draw the conclusion that this is the cause of the separation of the different colours. The red rays being least liable to bend—least refrangible—take up a position not much above that which they would have occupied had they been allowed to pass direct without the interposition

of the prism, while the blue rays, being more refrangible, are bent a long way out of the straight path, and so are found on the screen some way above the red.

The reason for using a small aperture is also apparent. With a large one, rays from different parts of it would fall at different angles on the prism, and the colours would, in consequence, overlap, and be more or less varied, giving a very impure spectrum. This may be proved at once by enlarging the hole. If it is made large enough, we shall find that the colours in the middle of the spectrum are sufficiently mixed to produce white light again, and we shall have only a fringe of blue at the top and of red at the bottom. There is however no objection to our enlarging the aperture in the direction parallel to the lower edge of the prism, so as to broaden our spectrum without lengthening it. By using a slit, parallel with the edge of the prism, instead of a mere hole, we shall only broaden the band of coloured light, and this we may do to any extent that the length of the prism will admit. If we are using an artificial [1] light we shall find that, however much we may spread out the spectrum, it is always continuous. There are no gaps. We may weaken it down, but we can never separate the red from the yellow, the yellow from the green. This shows us that there are in the spectrum rays of all possible refrangibility, and consequently of every hue, passing from red gradually to violet. It is usual to speak of the *seven* colours of the rainbow or the spectrum, but this is misleading. The spectrum is not made up of seven distinct bands of colours, but is one continuous even gradation of rays, which as they alter in character gra-

[1] The reason for this limitation will appear hereafter.

dually, so gradually change the effect they produce on the eye.

Newton was the first to divide the band of the spectrum into seven colours, and to give those colours the names they now bear, for his classification has been generally adopted,[1] though exception has been taken to his name of indigo, and other names for this colour have been suggested. As a matter of fact, however, it would be equally correct to divide the spectrum into four, which we might name Red, Yellow, Green and Blue, treating the orange as a shading of the Red into the Yellow, and considering the three varieties of Blue as one, or even into three, Red, Green, and Blue, which, when we look at the spectrum, certainly appear to the eye the most prominent hues. This is merely a matter of convenience, but as it is convenient that everybody should adopt the same system, the mystic number seven is likely to remain undisturbed.

When we have realized the fact that white light contains within itself this infinite variety of colour, it is not difficult to conceive how it is that it possesses the power of giving to various objects the colours which we recognize in them.

If we hold a piece of red glass in the beam of a lamp, we shall see that the light which passes through it is red. The light is red if we look directly at the source of light

[1] Some ingenious individual has suggested that those who find it difficult to remember the order of the spectrum colours may assist their memories by thinking of the following sentence, "Read Over Your Good Book In Verse," the initial letters of the words of which correspond with the initials of Red, Orange, Yellow, Green, Blue, Indigo, Violet.

through the glass, or if we allow the light to fall on a sheet of white paper. The natural idea would be that it was coloured or stained red by passing through the glass. If, however, we hold it between the source of light and the prism forming a spectrum, we shall at once see that the redness is due, not to any addition to or alteration in the light, but to the removal of those rays which cannot produce the sensation of red. The green light is much dimmed, the yellow, the blue, the indigo and violet, are probably gone. The red and orange are as bright as ever. Blue glass will probably leave visible only the blue, the green, and a patch at the end of the red.[1] We see therefore that the colour of the glass as viewed by transmitted light is due to the fact that it allows red light to pass while it cuts off most of the rest of the spectrum. We are also led to a very important observation, viz., that the colour is due, not to the rays of one part of the spectrum alone, but to the rays from several parts united together, and we realize the fact, that by commingling light from certain parts of the spectrum, and by suppressing the remainder, we may obtain colours differing from those in any part of the spectrum itself. There is, however, no colour, there can be no colour in existence, which cannot be matched by combinations of coloured light sifted out from the spectrum.

If, instead of interposing a transparent body in the path of the light, we take a brightly coloured opaque body, such as a piece of scarlet cloth or blue paper, and

[1] The actual result depends upon the precise character of the glass. Some red glass allows a good deal of blue to pass, some cuts it off almost entirely, some lets through a large amount of green, some blue glass lets through a good deal of red.

pass it along from end to end of the spectrum, so that it is illuminated in succession by each set of rays from the red to the violet, we shall find that the red object shines brilliantly in the red and yellow rays, but appears absolutely colourless—black—in the green and blue, while the green object, illuminated by the red light, shows black, shining brightly only when it is exposed to the green and the yellow. Hence we are justified in assuming that opaque objects show colours because they reflect certain of the rays which fall upon them, and absorb (since they certainly do not reflect) the remainder.

The generally received theory is that the light penetrates a certain inconceivably minute distance below the surface of the coloured object, and that, as it is reflected back, a portion of it is absorbed by the film through which it has penetrated, the colour of the object being due to the character of the light which is not absorbed. Thus, that when white light falls on a leaf, it penetrates into the outer film of its substance. As it is reflected back the red and blue rays are absorbed by that film, the green and yellow pass through unaffected, and thus the light which reaches the eye is green. We know that all substances, if sufficiently thin, become transparent, or rather translucent. Thin films of gold and silver even allow light to pass. Perhaps this may be considered an argument in favour of the proposition that all substances showing colour admit the penetration of light to a minute depth.

The above experiments, it may be mentioned, can be performed in another way, without the use of the spectrum, by simply examining coloured objects in variously coloured light. If the light from a lantern, in front of

which has been fitted a piece of red glass, be thrown on a number of pieces of differently coloured paper, it will be at once seen that the blues and greens will look black, the reds and yellows bright, and so with other colours. The results will not be as good as with the colours of the spectrum themselves, because, as was seen from the former trials, colours obtained by absorption, by passing light through coloured media, are never pure, and most red glass, for instance, will allow a small proportion of the blue rays to pass which will suffice to give a blue tone to objects capable of reflecting those rays.

But if a pure monochromatic[1] light be employed, the experiment may be carried out as effectively as with the spectrum. Such a light may easily be obtained by throwing salt into burning spirits of wine. This gives an almost pure yellow light, and therefore it robs every object of every colour but yellow. A bunch of ribbons or of strips of coloured paper looked at in this light shows no colour but yellow. Green and red become dull tints of yellowish grey, blue and purple look black.

By these and other similar experiments we are forced to the conclusion that objects have no colour in themselves. That they appear coloured to the eye is due merely to the fact that they have the power of absorbing some of the rays which go to make up white light, and reflecting, or (in the case of transparent objects) transmitting, the remainder. Some transparent substances reflect the rays they do not transmit, so that they are of different colours, according as they are viewed by reflected or transmitted light. Many of the aniline colours

[1] "Of a single colour only," derived from two Greek words signifying respectively "single" and "colour."

have this property. If a drop of the common red ink now generally sold be allowed to dry on a piece of glass, it will still appear red when held up against the light, but when looked down upon it will look green.

Other bodies show the same, or nearly the same, colours under either condition. In all cases, however, it must be taken as an axiom that bodies showing colour obtain it by selection from the white light falling upon them, and not because it is an inherent property of their own. Why many surfaces, to all appearances identical, show such varied colours; why other surfaces by no means resembling each other appear identical in hue; these are problems of which no solution has yet been discovered. We can only assume that they have certain definite characteristics, the nature of which we are yet unable to conjecture.[1]

It may indeed be objected that no proof has yet been offered that the effect of passing light through the prism was to decompose the light, to separate it into its constituents. It might be imagined that the action of the prism on the light had been such as to change its nature in some way, and to cause the colours to appear. Proof positive, however, is afforded of the truth of the theory by the fact that if we take all the colours and mix them together again, we get white light as before. This mixing may be effected in various ways, as by interposing in the path of the rays a second prism, turned in the opposite direction to the first, or by collecting the rays by the use of a lens or a concave mirror,[2] or by arranging a number

[1] Even substances which are closely allied in their chemical nature sometimes show quite different colours.

[2] A plane mirror of thin glass may be so bent by the hands as to reflect the rays to the same spot and mix them.

of mirrors at such angles that they collect the scattered rays and bring them to one spot. By any of these devices we can recompose the decomposed light, and we shall always get white light.

More than this, we can make up white light by mixing together coloured lights (in proper proportions) obtained from any source whatever. If we spin round before the eye a card painted with the colours of the spectrum, the persistence of vision[1] will cause all the colours to be mixed in the eye. We shall lose all sensation of colour, and shall get, not indeed white, for no paints can imitate the brilliance and purity of the hues of the spectrum, but a grey, more and more tending to white as the colours are brighter and more accurately proportioned.

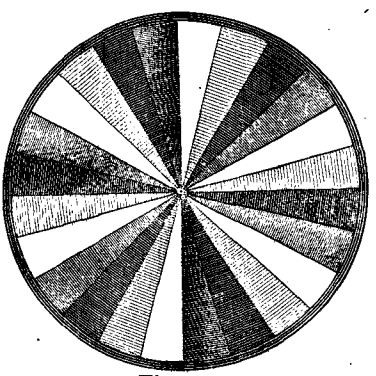

Fig. 34.

Discs suitably coloured may be purchased from the instrument makers, or they may be made by pasting strips of coloured paper —red, orange, green, and blue—radially from the centre

[1] When a bright object is seen by the eye, the impression remains for a certain definite length of time. If a stick, the end of which has been lighted and is glowing, be whirled round in a circle, the eye sees a circle of light, or portion of a circle, according to the rate at which the stick is whirled. A rapidly revolving wheel appears blurred. A shooting star appears as a line of light, so does a lightning flash. The duration of the impression has been calculated to be about the fiftieth part of a second.

to the circumference of a circular piece of cardboard. They may be spun on what is known as a whirling table,[1] a device in which a wheel turned by a handle (fig. 35) gives, by means of an endless cord, a very rapid motion to a smaller wheel on which the coloured disc is fixed. Or the disc may be secured to a reel slipped over a rod with a handle to it (fig. 36). A cord is wound round the reel, and by pulling the cord the reel is put into rapid rotation, just as a top is spun.

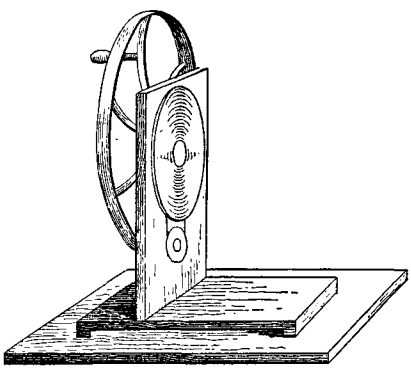

Fig. 35.

By placing a card with a slit in it in the path of the rays which have passed through a prism, any of them can be separated, so that we shall have pure light of any desired hue from any part of the spectrum. By this means we can take light from two or more parts, and, by means of additional prisms or lenses or reflectors, mix it together, thus obtaining fresh combinations

[1] Captain Abney employs for this purpose a little electro-motor, which by its evenness of rotation gives very good results.

of colour, some of which are not to be found in the uncombined colours of the spectrum itself. Certain of these mixtures we shall find suffice to produce white. Amongst these it should be noticed that blue and yellow will be found. It may be considered that this statement that blue and yellow produce white is contrary to experience, which teaches us that blue and yellow make green. Nevertheless it is true. Blue and yellow light mixed together make white light. On the other hand, the popular belief is true, too, when properly limited.

Fig. 36.

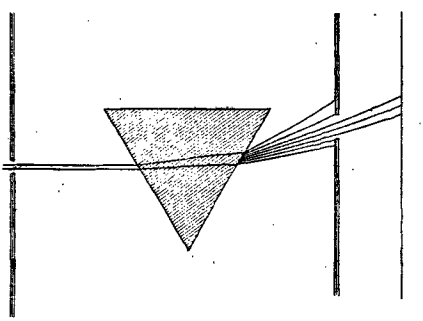

Fig. 37.

Blue and yellow pigments mixed together make green pigment. Blue and yellow glass held up against the light throw a green shadow. The fact is not difficult to explain. Yellow pigment is yellow because it absorbs the red and blue light, reflecting for the most part yellow and green. Blue pigment is blue because it absorbs yellow and red, reflecting blue and some green. When the two are mixed the yellow absorbs red and blue, while the blue absorbs the yellow; the green is still reflected, and the mixture is therefore green. So with

the glass, the green is the only colour which survives the passage of the yellow and blue glasses, all the rest being absorbed.

The effect of mixing coloured lights can also be shown without a spectrum, by the help of the copying arrangement described on page 32, and a few pieces of brightly coloured paper. If a piece, say of blue paper, be laid on one side of the vertical piece of glass, so as to be seen by reflection, its image can easily be superimposed on a bit of yellow paper looked at through the glass. If the colours are well selected and vivid, their union will

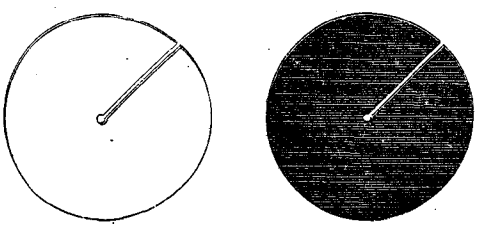

Fig. 38.

give a greyish tint, coloured probably by whichever, blue or yellow, is the stronger, but it will certainly not be the green which would be produced by a mixture of the pigments with which the papers were coloured. If the bits of paper be specially painted, a third piece can be painted with a mixture of the paints employed, and the difference will be seen at once.

Another mode of combining colours, and one that is of frequent use in experimental work, is by the use of the revolving discs previously described. Discs of cardboard are prepared of the required colours, either by painting them, or by covering them with paper of the

desired tint. If these discs are then slit from the centre to the circumference, in the manner shown in fig. 38, several can be placed on the spindle of the whirling table, interlaced together as indicated in the diagram, fig. 39, and by causing the edge of the lower one to overlap more or less through the slit of the upper one, more or less of it can be shown, and the desired proportion of its colour obtained to mix with the colour of the upper one. Thus two colours can be compounded in any proportions wished. If desired, other discs can be

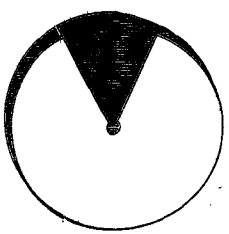

Fig. 39.

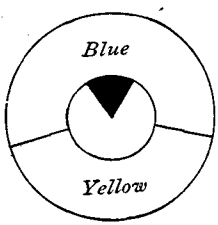


Fig. 40.

added in the same manner, and the effect observed of combining any number of colours.

This simple but ingenious device is due to the late Professor Clerk Maxwell, and the discs thus arranged are known as Maxwell's colour discs. By arranging discs of different sizes on one spindle, different combinations of colour can be compared. Thus, if a small pair of black and white discs be placed, as shown in fig. 40, on the same spindle with a blue and yellow disc, the grey produced by the latter can be accurately matched by adjusting the former. The reason why we get a grey, not a white, is simple enough. If we rotate a disc of

white paper, we get white light reflected from its whole surface, just as though it were standing still; but if we rotate the combined disc, we have blue light from one portion and yellow from the remainder. We lose all the blue light which the yellow surface absorbs, all the yellow which the blue absorbs. The result, therefore, is as though the light falling on about half the surface of the disc had to illuminate the whole.

So if we mix Red, Blue and Green about in the proportions indicated in fig. 41 we shall get a grey which we may match as shown with black and white. Blue, green and yellow (fig. 42) will also give white. Red and

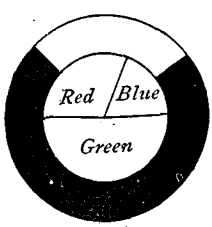

Fig. 41.

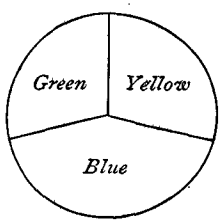

Fig. 42.

green with the amounts shown in fig. 43 of black and white, form a perfect match for a disc of ordinary brown paper.[1]

There is, in fact, hardly any end to the combinations which may thus be made. Till the experiment is actually tried, it seems hardly possible to believe that the bright colours of the inner sectors of such a combination as that of fig. 41 will produce a tint absolutely indistinguishable from that formed by the mixture of the black and white of the outer ring. Few physical experiments are

[1] Abney.

more easily made, few are at once so impressive and so instructive.

From the belief that all the colours of the spectrum could be made up from three—red, blue, and yellow—came the old idea of three primary colours. Modern investigation has shown that no three colours have any right to this title. No doubt, if our senses were capable of appreciating such minute differences, each separate ray, as it differs from its neighbours in refrangibility, would differ also from them in colour. There is, however, justification for the belief that we may speak of

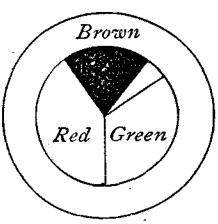


Fig. 43.

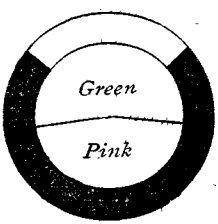


Fig. 44.

three colour sensations, since the colours of the spectrum may all be matched to the eye by mixtures of three colours, red, green, and blue, but even with regard to these it is better to avoid the misleading term "primary colours."

If the Newton's disc be placed on the whirling table, and any one of the colours be covered up by a piece of black card, we shall have on rotating the apparatus, not white, since one of the components of white light will be absent, but a colour produced by mixing all the colours of the spectrum *minus* the excluded one. If we cover up the yellow, we shall have violet; the removal of green

leaves purple; on taking away the blue, there is left orange. Each of these colours is termed the *complementary* of the one that was covered up. Thus, yellow is complementary to violet, green to purple or pink, blue to orange, and *vice versâ*. That is to say, each of these pairs, combined together, will produce white.

This may be practically demonstrated by placing discs of complementary colours on the whirling table and combining them. Fig. 44 shows the arrangement in the case of one pair of complementaries, green and pink.

Very many elaborate attempts have been made to classify colours. The pure spectrum colours were termed primaries, hues produced by a mixture of two spectrum colours secondaries, while the name tertiaries was given to a mixture of three pure colours. It was evident that in the last class white light must be present, as its elements were there, and that the tertiary colours might be considered as a mixture of two pure colours with a proportion of white light. But it is also possible to match any colour by adding white light to or lessening the luminosity of, a single one only of the spectrum colours, and on this principle Captain Abney has lately devised a most ingenious method of practically matching colours, so that any tint whatever can be recorded by a formula which will admit of its reproduction at any future time. It is only necessary to state the precise point of the spectrum where the required pure colour is to be found (and this can be done with absolute accuracy) and the proportion of white light to be added.[1]

[1] In the case of purple tints it is only possible to match the complementary colour, and thence to deduce the colour itself. A full description of the method is given in Abney's "Colour Measure-

It is well known that if we stare hard for some time at a brightly coloured object—stare, in fact, until the eye is a little tired—we shall see, on looking away, a sort of phantom or ghost of the object, but of a different hue. The colour of this phantom will be complementary to that of the original object, and the reason is not far to seek.

After the eye has been for some time looking at a bright colour, say red, it becomes tired of red, and consequently insensible to light rays of that colour. Then, when white light enters it, it perceives all the other rays more vividly than red, and the same result is produced in it as was produced with the Newton's disc when the red was covered, white light *minus* red or the complementary of red, viz., green.

To discuss at any length the cause of this fatigue of the eye would take us too far into the domain of physiological optics, but it may just be mentioned that it is believed that there are in the retina nerves sensible to each of the three colours, red, green, and blue. Light containing all three colours, in whatever proportions, excites all three sets of nerve fibrils in corresponding proportions; light containing two of the colours excites two sets of fibrils, and of course light of one colour excites only the set of fibrils sensitive to that colour. This is the reason why we apparently have a right to speak of three primary colour sensations.

This theory, too (first propounded by the great German physicist Helmholtz), gives us an explanation of the

ment, and Mixture," published while the present book was passing through the press.

cause of colour blindness, for it is supposed that colour-blind persons are deficient in one set of nerve fibrils, and are consequently incapable of perceiving the colour associated with that set, whether alone or in combinations with other hues. Thus a red-blind person is not only lacking in the power of appreciating the shades of red itself, but he sees all shades in which red occurs as if the red had been taken out of them.

An easy way of experimenting with these "accidental," or, as they are now called, *negative* colours, is to lay on ground of one colour a slip of paper of another colour, and then, after looking for a few seconds at the small slip, to twitch it away by a piece of string previously attached to it. We shall then get an image the colour of which will depend on that of the slip and of the background, on the latter indeed as much as on the former. If the background be a sheet of grey paper, we shall, on the removal of the small piece, see an image of the complementary colour, or nearly the complementary colour, for as the eye is only rendered less sensitive, not entirely insensitive to the colour of the slip, it will still receive a certain amount of light of that colour, and to that extent the brilliance of the image will be dimmed. Thus, if we use a green strip on the grey background, the image will be a pale rose, because nearly but not all the green component of the light reflected from the patch of background previously covered by the slip is ineffective to the eye.

The results are somewhat varied if, instead of grey, we use a sheet of coloured paper for a background. Suppose, for instance, we place the green slip on a yellow sheet, then when it is removed we shall find its place oc-

cupied by an orange image, that is to say, an image of a colour compounded of the complementary and the tint of the background, rose and yellow making orange. In this latter class of experiments the eye is partly deceived by the effect of *contrast*, so that the judgment is to some extent at fault. The effect of adjacent colours on one another is well known and very curious. It may be taken as a remarkable proof of the untrustworthy character of the eye as a judge of colour. The fact may be illustrated by many experiments. If a slip of pale bluish-

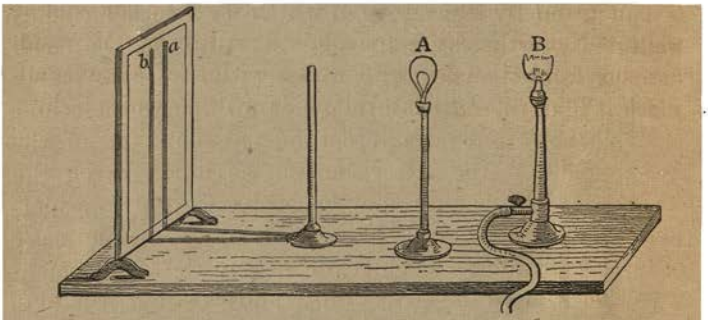


Fig. 45.

green paper be laid on a sheet of paper of the same tint but darker, it appears grey, whereas a piece of really grey paper laid beside it will look reddish.[1]

A familiar instance of this deception of the judgment is afforded by the (apparently) differently coloured sha-

[1] The account of the above experiments is taken from Rood's *Modern Chromatics*. He gives a fuller account of them, and describes several others. The subject of the effects of contrasted colours in relation to design and to painting is a most interesting one, but it cannot well be discussed further here.

dows thrown by an object illuminated by lights of two different colours. Notice, for instance, the shadows of a railing, produced on the pavement by the moonlight and the light from a street lamp. The shadows thrown by the moon will look yellow, those by the lamp blue. The experiment can be made in the way shown in fig. 45, in which a rod is caused to throw two shadows, one *a* produced by the electric lamp *A*, and one *b* produced by the gaslight *B*. The shadow *a* is of course illuminated by light from *B*, which is yellowish, while the shadow *b* is illuminated by light from *A*, which we may consider as white. Nevertheless, the shadow *b* will look, not white, but blue, from the effect of contrast with the background, which is illuminated with yellow as well as white light.

## CHAPTER V.

### INTERFERENCE AND DIFFRACTION.

Wave lengths.—Interference of waves.—Colours of thin plates.—Soap films.—Diffraction.—Gratings.

FROM all these observations, we are led to doubt the testimony of the eye as regards colour, and to ask what is indeed that difference between the rays of light at the two ends of the spectrum which produces in our eyes the sensation of colour. The question is easily answered, though the proof of the truth of the answer it is not so easy to give in a simple and intelligible form. We must revert to our original consideration of the nature of light; and it may be observed that, whereas most of the phenomena previously dealt with could be equally well explained whatever theory of the nature of light were adopted, we are now dealing with phenomena of which no intelligible explanation has ever been given except on the theory that is generally adopted by all scientific men, that light is caused by vibrations of something which is termed the ether. White light is composed of vibrations of every size between the limits which affect the eye, but if only vibrations of the same, or nearly the same length, are admitted to the eye, they produce the effect of colour, giving one or other of the pure colours of the spectrum. When we speak of mixing

colours, therefore, what we have really been doing is to admit to the eye vibrations of a certain series of lengths, while excluding those of the other lengths. Now these vibrations, it must be understood, are inconceivably minute in size. Of those at the extreme red end of the visible spectrum there are no less than 37,000 to the inch; and those at the violet end are much shorter still, for in every inch there are 65,000. As there are 63,360 inches in a mile, each wave length at the violet end bears just about the same relation to an inch that an inch does to a mile. That may give us some notion of their size.

And if they are of such extreme minuteness, so are they also of a rapidity equally beyond the powers of our mind to realize, for the vibrations take place at the rate of four hundred and fifty millions of millions per second at the red end, and seven hundred and ninety millions of millions at the violet end (as many in one second as there are seconds in about 25,000,000 years). These enormous figures convey no idea to the mind beyond that of very great magnitude, but it must not be imagined for that reason that there is any doubt about them; they are just as real measurements as that of the distance of the earth from the sun. Both are matters of calculation, and there is no more reason to dispute the accuracy of one than of the other. Both calculations are liable to correction, because more and more exact observations are made from time to time to determine the quantities on which they are based, but that any serious alteration will ever be made in either one or the other is highly improbable.

In all wave motion, whatever its character, there is one special feature: when two systems of waves meet they will interfere with each other as they pass across or

over each other, and will produce at the points where they cross or meet a result differing from that produced by either system singly.

According as the elevations and depressions coincide or are opposed, so will the size of the waves be increased or diminished. If the waves are crossing each other at an angle the case becomes complicated, but let us consider the simplest case, of two similar waves moving in the same direction, but not necessarily in the same "phase," or as we may call it, not necessarily of the same height at the instant of starting. We can represent diagrammatically what occurs.

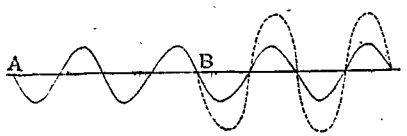

Fig. 46.

Suppose first, as in fig. 46, a wave starting from *A*, and suddenly reinforced at *B* by a second similar wave. The result will be that the effects of the waves may be added together, or, which is the same thing, since the waves are similar, the effect will be doubled. In water the waves will be double the height, with sound the sound will be twice as loud, with light the light will be twice as bright. This is shown in the diagram by the dotted line, which, if the full lines represent the wave motion above and below the normal level, represents the sum of those motions. This case is also evidently the one in which one wave is exactly a whole length behind the other.[1]

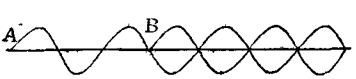

Fig. 47.

[1] It must be remembered that these representations are purely conventional. They are meant to assist the student in grasping the

Now consider the case in which a wave starting from *A* has suddenly superimposed upon it at *B*, fig. 47, a second similar wave, but in the exactly opposite phase, the particles of which are rising just as those of the first wave are falling, and *vice versâ*. Such a wave is evidently half a wave length behind the other. Then taking the height of the wave-line at any point above the base-line as a *plus* quantity, and the depth below as a *minus* quantity; and adding them together, we shall get zero in all cases as our result. At every point the depression of one wave annuls the elevation of the other, and we get no movement whatever. That is to say, with water we get stillness, with sound silence, with light darkness. Such is the theory, now for the experimental verification.

It is not easy to realize the fact that two lights can make darkness, but under special circumstances it is so; only indeed under special circumstances, for we have not sufficient command over the forces of nature to enable us to do more than produce the special results we seek under very limited and closely confined conditions. For instance, we must use monochromatic light, which will of course be light composed of vibrations of about the same magnitude. If, using such light, it be possible so to arrange an experiment as to produce darkness or dark spaces where two rays of light fall, of which rays one consists of vibrations half a wave length behind those of the other ray, we shall at all events have obtained one

idea of wave-motion, not to serve as a picture of what really happens. The misuse of such diagrams leads to what has been wittily termed the "corrugated zinc theory of light," a theory by no means to be encouraged. Properly understood, however, they are very serviceable.

strong piece of evidence in favour of the undulatory theory, and also of what is known as the *interference* of light. As a matter of fact, there are many ways in which the result can be obtained. The simplest and most easily intelligible known to the writer is the one given by Professor Tait in his book on Light to the following effect.

*B C D* (fig. 48) is an isosceles prism of glass, with the angle at *C* very little less than two right angles (and the angles at *B* and *D* consequently very small). A luminous point is placed at *O*, in the plane through the obtuse edge of the prism and perpendicular to its base.

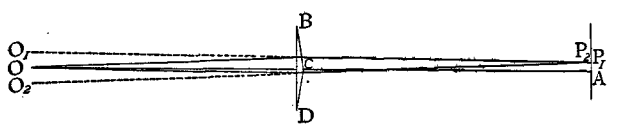


Fig. 48.

The light from *O* (homogeneous [1] light being used) will by refraction through the prism, or rather through the two halves of the prism, be bent so that it diverges as if from points $O_1$ and $O_2$ symmetrically situated on either side of the line *C O*.

Suppose a sheet of paper to be placed at *A* with its plane perpendicular to the line *O C A*, let us consider what illumination will be produced at different parts of this paper. As $O_1$ and $O_2$ are images of *O*, crests of waves must be supposed to start from them simultaneously. Hence they will arrive simultaneously at *A*, which is equidistant from them, and there they will reinforce one

[1] Homogeneous here has the same sense as monochromatic, it means all of the same character.

another. Thus there will be a bright band on the paper parallel to the edges of the prism.

If $P_1$ be chosen so that the difference between $P_1 O_2$ and $P_1 O_1$ is half a wave length (*i.e.*, half the distance between two successive crests), the two streams of light will constantly meet in such relative conditions as to destroy one another. Hence there will be a line of darkness on the paper, through $P_1$ parallel to the edges of the prism.

At $P_2$, where $O_2 P_2$ exceeds $O_1 P_2$ by a whole wave length, we have another bright band; and at a point $P_3$, where $O_2 P_3$ exceeds $O_1 P_3$ by a wave length and a half, another dark band, and so on.

Hence, as everything is symmetrical about the bright band through $A$, the screen will be illuminated by a series of alternate parallel bright and dark bands, at approximately equal distances from one another.[1]

The interval between any two bands will increase very nearly in proportion to the distance of the screen from the source of light, while the intensity of the bands diminishes rapidly as the screen moves further off. To measure the distance between the bands the eye should be put in place of the screen; when this distance and the length $O A$ have been measured, it is possible (from the known material and form of the prism), to calculate the distances $O_1 P_2$ and $O_2 P_2$. The difference between the two is the length of a wave of the homogeneous light experimented with.

As is pointed out by Professor Tait, this experiment, though not the method actually employed, its results not permitting sufficient accuracy, shows very clearly and simply the possibility of measuring a wave length. It is

[1] Tait's *Light*, p. 186.

principally for this reason that the description of it has been transferred to these pages.

If instead of homogeneous light we use white light, the problem will be very much more complicated, owing to the overlapping of the different spectra; the result, however, will be that we shall have bars of bright light on the screen, fringed on either side with the colours at the ends of the spectrum, viz., red and violet. Thus we see that we may get colour by means of interference. And going a little further, it is not difficult to conceive that if by any means we can cause certain of the rays of the spectrum to obliterate themselves by means of interference, the colours that are left unaffected will combine, and we shall thus get a great variety of mixed hues. As a matter of fact, it is by this means that some at all events of the most gorgeous colour phenomena in nature are produced.

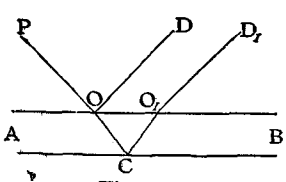

Fig. 49.

Supposing a ray of light *P O* to fall at an angle on a thin transparent plate *A B*, we know that a portion *O D* will be reflected from the upper surface of the plate, and that another portion *O C* will pass into the plate, will be reflected from the inner surface at *C*, and (after suffering two refractions) will pass out into the air in a direction $O_1 D_1$ parallel to that of the first reflected portion. If the plate be a film so thin that the two reflected rays are close together, and also of such a thickness (or rather thinness) that the second reflected ray is caused to lag just half a wave length of any coloured light behind the first reflected ray, the light of that colour will be cancelled, and

the reflected beam will be tinted with a hue composed of the balance of the colours making up white light, that is to say, with the complementary colour of the one abolished. Thus, if the red be eliminated, we shall get a greenish blue; if the green be taken out, we shall get purple.

The qualities required to produce interference colours are found to perfection in a common soap-bubble film, the variety of colours which a soap-bubble shows being due to the different thicknesses of different parts of its film, and the changing play of those colours to the constant changes in thickness which the film undergoes. At one part of the surface the film is just thick enough to destroy the red rays, at another the blue, at another the green, and so we get the complementary hues of these colours and various intermediate tints. For experimental purposes the films are best made of a solution of soap and glycerine, or oleate of soda and glycerine, and on little wire rings instead of in the shape of bubbles.[1]

When a flat film of this sort is illuminated with a powerful beam from the electric lantern, and the magnified reflection thrown upon a screen, a spectacle of the most gorgeous character is presented. As the film gradually thins by the downward drainage of the liquid, bands of exquisite colours—red, yellow, green, blue, and purple—pass in succession over the screen. If a jet of

[1] Many receipts for soap solutions have been given. Plateau's is simple: 1 oz. oleate of soda, 40 oz. warm distilled water, 30 oz. glycerine. As a rule the addition of soap is necessary. Wright recommends the addition of about ½ oz. soap (Castile) to the above, and gives detailed instructions, to which the student may be referred. For elementary experiments a moderately strong solution of soap gives quite satisfactory results.

air be blown against the film, the colours are all broken up into spires and whorls of even greater beauty still, affording a more interesting play of colour and a seemingly greater variety of charming hues.

The colours of thin films were first investigated by Newton, who employed a large lens pressed into contact with a piece of flat plate glass. The film of air between the two was, owing to the curvature of the lens, of gradually increasing thickness from the centre outwards. The arrangement is shown in the diagram, in which *A B* is a lens touching the flat plate *C D* at *E*. In white light we get a series of coloured circles; with monochromatic light a series of bright circles of the colour of the light employed separated by dark spaces. In either case the circles as they recede from the centre become narrower and closer together, in consequence of the rapidly increasing depth of the film of air, until it becomes too thick to give interference at all. An attempt is made in fig. 51 to represent the appearance presented by these rings in monochromatic light.

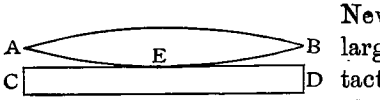

Fig. 50.

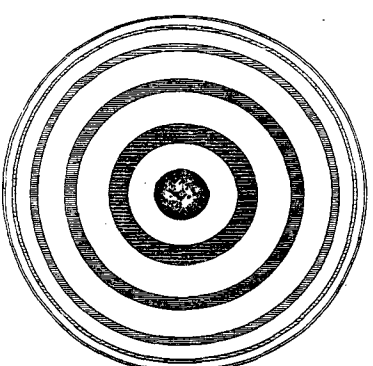
Fig. 51.

Minute as the quantities were, Newton succeeded in calculating the distances between the two glasses at the

points where the various rings were formed with monochromatic light, though his non-acceptance of the undulatory theory, which had already been suggested by Huyghens, prevented him from discovering their cause.

Newton's experiment may be roughly repeated by pressing together two wet pieces of glass. At some point in their surfaces, the film of water will probably be of such thinness as to give bands of interference colours. In this case, however, the surfaces will be too irregular to give us circles. We shall get unsymmetrical rounded shapes, more or less circular, and the bands of colour will be narrow. They will, however, suffice to show the phenomenon.

Or if a bit of the thin glass used for microscopic purposes be squeezed with the fingers against a piece of ordinary window glass, patches of colour and irregular rings will be seen, where the film of air is of the proper thickness.

Any thin films will serve to show interference colours. Greasy scum on the surface of a pond often shows streaks and bands of gorgeous colour produced in this way. Turpentine or oil on water shows them. If a drop of turpentine be floated on the surface of water in a basin, as the drop spreads out into a thin film the colours will show brilliantly. When steel is "tempered," it shows various colours produced by the film of oxide formed on it, amongst others the brilliant blue which watch-springs and other steel articles often exhibit. For the same reason a ladle of melted lead offers a most brilliant play of colour as the films of oxide of different thicknesses are formed upon the surface of the metal.

If we watch ripples in water striking against the edge

of any obstacle, we shall see that the ripples, as soon as they have passed the obstacle by, tend to flow round behind it. Sound waves also, as we know, will flow round an obstacle such as a pillar, and are audible behind it. These results, indeed, follow from the very nature of wave motion, for we must remember that we have to regard a wave, not as the result of a single impulse continually propagated in one direction, but as the result of an infinite number of impulses, tending to start waves in every direction. To put it crudely, we may say that when there is no obstacle all these impulses are forced to coalesce into a single forward-moving wave, but when by the intervention of a solid body these impulses are checked on one side, those on the other side are no longer balanced, but are left free to flow towards the obstacle. Directly that the obstacle is passed, they do so, flowing round behind it.

The belief that light rays did not thus bend round an obstacle was one of the principal objections to the undulatory theory, and it was this which prevented its acceptance by the great Newton. Young, however, showed that the bending actually does take place, and that the coloured fringes often seen at the edge of an object when looked at against a bright light, are due to this bending and the interference phenomena associated with it.

If a narrow slit in a blackened card, held up against a bright light, be looked at through a scratch made by a needle on a piece of smoked glass,[1] a bright image of the slit will be seen, while on either side of it extend a series of spectra, those nearest the centre fairly bright, while those further and further away become dimmer and

[1] Wright.

are drawn closer together, until at last they are indistinguishable. If light of one colour be employed, we shall get bands of that colour separated by intervals of darkness. Of these the central band is the brightest, consisting as it does of light passing direct through both slits to the eye.

Suppose $A\,B$ to be a section through the slit through which we are looking, $O$ being its centre point. A ray falling perpendicularly on the retina may be represented by $O\,R$, and the distances $R\,A$ and $R\,B$ will be equal, but for any other point on the retina the distances from the two sides of the slit will not be equal. Let us consider the point $R_1$, where the distance $A\,R_1$ is exactly a wave length more than $B\,R_1$. $O\,R_1$ is intermediate between the two. Either $A\,R_1$ or $B\,R_1$ will be half a wave length different from $O\,R_1$, and will therefore cancel it. More than this, as a little consideration will show, the rays on one side of $O\,R_1$ will cancel the rays on the other side, and we shall get a band of darkness. On the other side of $R$ another similar spot will be found, $R_2$. Beyond these again, on either side, we shall come to points where the difference between the distances from the two sides of the slit will equal three half wave lengths, and here it may be shown that only part of the rays will destroy each other, and we shall have a bright band. And so we shall find that wherever the difference is an even number of half wave lengths we shall get darkness, where it is odd we shall get light.

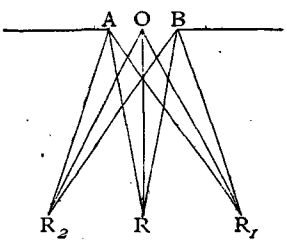

Fig. 52.

If, instead of a single slit, we have a number of parallel slits close together, the effect will be to strengthen the illumination of the bright spaces, and, if we are using white light, to give us a much brighter series of spectra than with a single slit. Then we have what is known as a "grating." Such gratings, ruled very finely and evenly, give spectra in all respects as good, and in certain respects better than can be obtained by the use of a prism.[1]

If, instead of ruling the lines on glass and using transmitted light, the lines be ruled on metal, and reflected light be employed, similar results are obtained.

It is obvious that the grating must be ruled with the greatest fineness and accuracy to give true results, but such gratings are made, and it is by their use that the wave lengths in different parts of the spectrum have been measured.

Many of the brilliant colours of natural objects are due to interference. Any finely striated surfaces show colours due to this cause. It is thus that the colours of mother-of-pearl are produced, as may be shown by taking an impression of a bit of the shell in sealing-wax, when the wax will show the same effects. The colours of some birds' feathers and the sheen on the plumage of others is due to interference produced by the texture of the feathers. The colours with which the motes in a sunbeam are illuminated owe their origin to the same cause.

Even so superficial an account as this of the chief phenomena of colour may serve to indicate to the student a conclusion to which he will be irresistibly drawn by

[1] These gratings are ruled with 3,000, 4,000, 6,000 and even 12,000 or more lines to the inch.

more extended researches, and that is, that not only is the eye utterly untrustworthy as a guide to colour, but that colour, as we perceive it, has no existence external to ourselves. It is purely subjective. The mechanical impulses which strike the eye are by it translated into the sensations which we know as colour. If these impulses strike the eye at the rate of about four hundred and fifty millions of millions in a second, we get the sensation of red. If they strike the eye at the rate of about seven hundred and ninety millions of millions, we get the sensation of violet.

Those of intermediate speed produce, alone or in their infinite combinations, all the colours which the eye has the power of appreciating. How it is that the eye is enabled to perceive colour is a question that we can hardly stay to discuss now, but it is as well to get this fact well into the mind, that colour is a purely subjective phenomenon. It is a sensation merely. To realize this clearly to ourselves is most difficult. We are naturally accustomed to regard the colour of a coloured object as a property of that object, and for all practical purposes we are quite right. But if we desire to get a clear view of the real cause and nature of colour, we must try and realize that when we speak of grass as green, we merely mean that the light reflected from the grass is light of a certain number of vibrations—it produces in the eye certain sensations which we call green.

It is hardly possible to realize the fact that the green of the fields, the blue of the sky, all the varied colours of nature exist, as one might say, in our own imaginations only—that colour is merely a sensation produced by feeling waves of greater or less magnitude strike the

eye. There may be at first a natural disinclination to admit the fact, but a very little thought shows us that we lose nothing by the knowledge. The hues of the rose are none the less beautiful, the glow of the sunset none the less bright, because we have some little knowledge of the causes which produce the effects we admire. On the contrary, we find an added pleasure in the colour of the flower or the glory of the sky, when, instead of merely gazing at them in ignorant wonder, we can admire not only the results which have been obtained, but the marvellous nature of the means employed to produce those results.

## CHAPTER VI.

### SPECTRUM ANALYSIS—THE RAINBOW.

Theory of Spectrum Analysis.—The Spectroscope.—Spectra of the elements.—Fraunhofer lines.—Spectrum Analysis applied to the Sun.—The Rainbow.—Secondary bows.

WE have already seen that, by interposing between the source of light and a prism any transparent coloured body, and then examining the spectrum formed under these conditions, we are enabled to examine, or indeed to *analyze* the light transmitted by the body. If we carried out a series of experiments with, say, a number of coloured glasses, we should find that some of the glasses, though of tints hardly distinguishable by the eye, gave spectra totally distinct, and further, that the same glass always gave identically the same spectrum, so that we could readily identify it, or match it, if desired, by means of what is really a simple experiment in *spectrum analysis*. We may go further than this, and, with proper appliances, we may apply similar tests to liquids contained in narrow flat-sided glass cells, and we shall discover that each liquid has its own characteristic spectrum, in which certain of the rays are blotted out. Diluted blood, a solution of potassium permanganate (the well-known disinfectant Condy's fluid), a mixture of wine and water, may all be made to look very like one another to the eye, but the spectrum of each is unmistakable.

And we may go further still. Instead of examining light which has been affected by passage through coloured media, we may apply like tests to any coloured light, and we shall soon discover its nature. If, for instance, we examine by means of the prism the light emitted by a salted spirit flame, we shall find that it consists solely of one bright band in the yellow which, under considerable dispersion, shows a double line. No other light at all is emitted. Conversely, we may feel sure that whenever any light examined by a prism shows this yellow band, and it alone, that light is produced by burning sodium—sodium being the elementary body which forms the base of common salt.

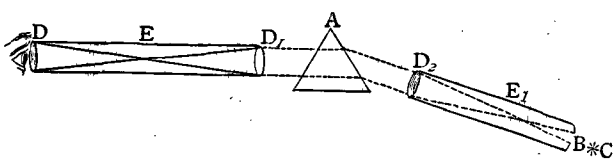


Fig. 53.

It is right to mention at once that even such simple experiments as those mentioned cannot be satisfactorily performed without special apparatus, and that for anything beyond the roughest demonstration of elementary facts, apparatus of considerable delicacy is required. In practical work the spectrum is not formed on a screen, but is received in the eye itself, the light being looked at through the prism and the slit. The diagram, fig. 53, shows the arrangement adopted in a simple spectroscope. *A* is the prism, *B* the slit, and *C* the source of light. $D_2$ is a lens (termed the "collimator") which serves to make the rays of light from the slit parallel before they

fall on the prism, while $D_1$ and $D$ are lenses which magnify the image. $E$ and $E_1$ are tubes which cut off stray light. In an instrument thus arranged the whole of the light is utilized, and a much more brilliant spectrum presented to the eye than when it is viewed by reflection merely.[1]

Researches with instruments of which the above is a simple type, have shown that all substances have their own characteristic spectra. A solid or liquid body when incandescent gives what is known as a continuous spectrum, a spectrum such as that we are now familiar with, but incandescent vapour gives a spectrum consisting of a series of bright lines only. All metals when volatilized by sufficient heat[2] give these discontinuous or bright-line spectra, each metal having its own distinct spectrum. The amount of heat required to volatilize them varies greatly. Sodium, as we have seen, volatilizes in the flame of a spirit-lamp. Potassium and calcium will volatilize in that of a Bunsen gas-burner. Many other metals require the heat of the electric arc. Some of the spectra are very simple, showing a few lines only; others are of great complexity, showing a very large number; but they are always the same for each element, so that a skilled observer is able to recognize them, and to say at once (at least in the case of well-known bodies)

[1] Those students who desire to see for themselves some of the simpler spectral phenomena cannot do better than follow out the instructions given in the chapter on Light in Weinhold's *Experimental Physics*. They will thus obtain a far better insight into their true nature than any amount of mere reading will give them.

[2] The continuous spectrum given by a gas or oil flame or the flame of a candle is due to the particles of incandescent carbon in the flame.

what the bodies are. This, then, is in brief the essence of spectrum analysis. The observer burns the substance to be examined, and, by observing the spectrum it produces, he is able to discover what the substance is. Thus several new elements have been discovered, because they gave spectra differing from those of any previously known elements.

Now it must not be forgotten what these bright lines are. They are simply images of the slit, formed by light of a certain refrangibility, and they merely show that all the other rays of the spectrum, the rays which would fill up the intermediate spaces, are absent, and that the light emitted by the substance at a high temperature consists of rays of a certain definite refrangibility, and none other.

In some of the very earliest spectroscopic observations of the sun's light, it was noticed that the spectrum was crossed by innumerable fine hair-like lines. These were first observed by Wollaston, and afterwards more carefully examined by Fraunhofer, from whom they are called "Fraunhofer's lines." It was soon seen that they indicated the absence of certain rays, and further investigation showed that some of these dark lines absolutely coincided with some of the bright lines previously seen in the spectra of metals; finally, experiment showed that when light from a source which would give a continuous spectrum was passed through a vapour which of itself would give a bright-line spectrum, the rays giving the bright lines were absorbed, and a spectrum with corresponding dark lines was the result.

Hence it was concluded, that since the sunlight showed dark lines corresponding to the spectra of certain terres-

trial elements, those elements were certainly to be found in some vapours through which the light had passed, and the conclusion was irresistible that the vapours were closely surrounding the sun itself, indeed in its outer envelope. The deduction followed that the central body of the sun must be either solid or liquid, and that it is surrounded with an outer atmosphere of heated vapours in which many of the telluric elements are present. Thus we may gain some idea how it is that the spectroscope enables us to gain a knowledge of the actual constitution of bodies at no matter how great a distance from us, provided only that light from them reaches us.

One important use of the Fraunhofer lines must not be

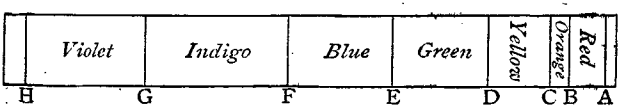


Fig. 54.

passed over. Their position is of course invariable in the spectrum, and they therefore provide the means of making a definite scale for the spectrum, and consequently of locating any point in it. Without their aid this would be quite impossible, as the boundaries between the different colours are far too vague and indefinite to serve for such a purpose with any accuracy. To say that a point in the spectrum is in the red, or between the red and orange, gives but a vague idea of its position; but if we say it is near such and such a line, its place is determined with absolute accuracy, and that whatever means may be used to form the spectrum. To enable this to be done conveniently, the principal lines have

been indicated by letters. A few of the more important are shown in the diagram (fig. 54).

Beautiful as is the spectrum as we can produce it in the laboratory or the lecture room, its beauty is of course far transcended by that most splendid of all natural phenomena, the rainbow. We all know that the rainbow is produced by the light of the sun falling on drops of rain, but it will be interesting to consider how it is that the drops have the power of decomposing the sunlight, and why it is that the bow or arch shape is always preserved.

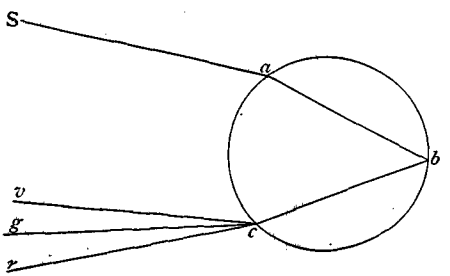


Fig. 55.

If, standing with your back to a light, such as a gas-burner, you look into a round bottle, say an ordinary chemical flask, filled with water, and held up over your head, you will easily find a position in which you will see the flame reflected as two spectra one above the other, the upper one having the red at the top, the lower one the red at the bottom. Precisely the same thing happens with a drop of rain when it is in that precise angular position to reflect the light of the sun back to the observer's eye. Fig. 55 shows us how the reflection takes place. The light coming from *S*, the

direction of the sun, falls on the surface of the drop at *a*. Some of it is reflected away, the rest enters the drop, being refracted as it enters. It passes on and strikes the back of the drop at *b*; here it is totally reflected and sent back out of the drop at *c*. In its

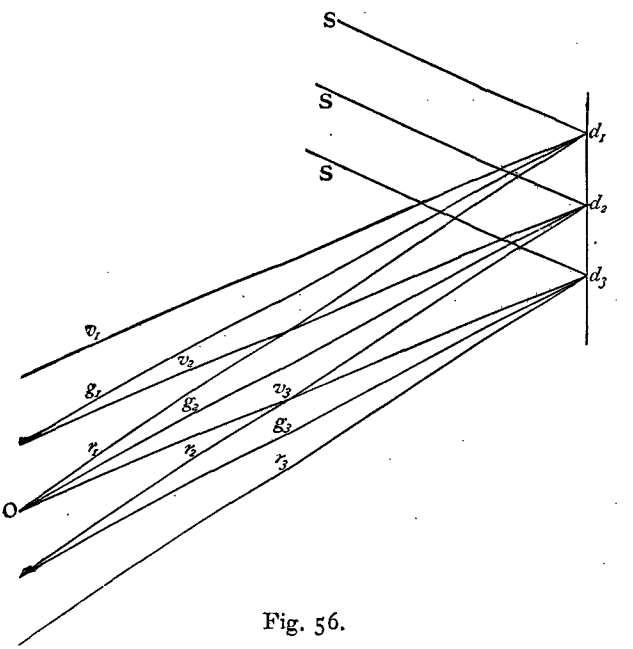


Fig. 56.

passage the ray has also undergone dispersion, so that the white light which entered the drop has been decomposed, and the ray as it passes out shows the usual prismatic colours.[1] It is evident that an observer, to whom

[1] For the sake of simplicity, no attempt has been made in the figure to indicated the path of the different rays through the drop.

the light is reflected, can only receive light of one colour from each individual drop. This is illustrated in fig. 56, in which $d_1$, $d_2$, and $d_3$ represent three drops one below another, and $O$ the eye of an observer. The drop $d_1$ can only send him red light, but somewhere below $d_1$ there will be a drop $d_2$, which will send a green ray, and below that again the drop $d_3$, which will send violet. All the other rays from these will be directed so that they pass by and are not perceived. It is hardly necessary to say that the reflections are not from single drops, but from the multitude of drops occupying about the same relative position with regard to the observer. This figure may also serve to show that no two persons can see absolutely the same rainbow at once; they see indeed precisely similar reflections, but not identically the same. In fig. 57 the course is shown of those rays which form the secondary bow often seen. It is formed by rays which are twice internally reflected, and therefore the spectrum is inverted.

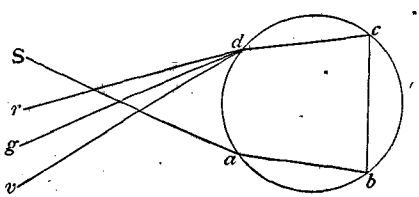

Fig. 57.

If an imaginary line be drawn from the sun to the drop, and another from the observer's eye to the drop, these two lines will inclose an angle of about 42°. All drops lying in such positions that lines drawn to them from the eye meet, at an angle of 42°, lines drawn to them from the sun will help to form a rainbow to the observer. It is obviously of no consequence whether they are above him, or on his right hand, or on his left. The innumerable lines which could be drawn under the

conditions named may be considered as forming a cone the apex of which is at the observer's eye. The base of a cone is a circle, and therefore a rainbow must needs be circular. Standing on the ground we can only see at most half of it, but people in balloons see the whole of the circle. The small bows formed by the spray of waterfalls, as we may see them when standing actually in the spray itself, are also frequently circular.

## CHAPTER VII.

### LENSES.

Action of Lenses.—Convergent and Divergent Lenses.—Formation of Images by Lenses.—Chromatic and Spherical Aberration.

IF we take a simple lens, an ordinary magnifying or reading glass, and hold it in the rays of the sun, we can concentrate the rays into a small bright spot. We are employing it as a burning-glass, possibly one of the earliest uses of a lens. If we place the lens close to a small object, and look through it at the object, the object is enlarged. If we hold up the lens opposite a window, and place behind it a sheet of white paper, we can obtain on the paper a reduced picture of the window, and the lens is then exemplifying the latest of all its applications, that of photography. How comes it that the same simple instrument should serve for such diverse uses?

To answer this question we must inquire into the nature of the action of a lens, and we shall find they all result from the manner in which the light rays are bent or refracted in passing through a symmetrically shaped body such as a lens.

The simplest way of arriving at a clear idea of the action of a lens is to consider it as built up of an infinite number of prisms. We have already considered the manner in which a prism refracts light falling

upon it. Take now the case of a narrow prism, in which the sides are not very far removed from being parallel. We shall then get less dispersion than with the larger prisms used to produce a spectrum. If we arrange two such prisms base to base, light starting from a point in a line with their bases will evidently be refracted downwards by the upper prism, and upwards by the lower prism, so that the paths of the refracted rays will cross. Let us consider only a pair of symmetrical rays, $P\,a$ and $P\,b$. $P\,a$ will strike the lens $A$, will be refracted to $a_1$, and then to $P_1$. $P\,b$ will follow a similar path through the lens $B$, $P\,b\,b_1$ $P_1$, reaching also the point $P_1$. So also a series of prisms might be arranged as in fig. 59, $b$, $d$, $e$, $f$, $g$, $h$, so as to converge rays from the point $P$ to the point $P_1$. It is assumed that they are all of the proper angle to do this. Such an arrangement would be represented by $A$ in fig. 60. Then, since it is the angle at which the sides of the prism are set, not the mere thickness of the glass, which causes the refraction, we may substitute $B$ for $A$, filling up the space $d$ with plain glass, through which the central ray will pass unrefracted as through the open space in $A$. Finally, we may round off the whole, and we get $C$, the well-known lens shape.

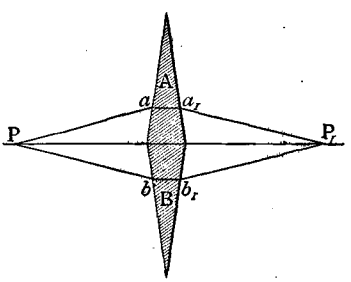

Fig. 58.

Lenses are divided into two classes, according as they are thickest or thinnest in the middle. In fig. 61, $a$, $b$, $c$ belong to the first, and $d$, $e$, $f$ to the second class. When

both the surfaces are convex, though not necessarily of the same curve, as in *a*, the lens is "double convex;" *b* has one flat side, and is called "plano-convex;" *c* is a

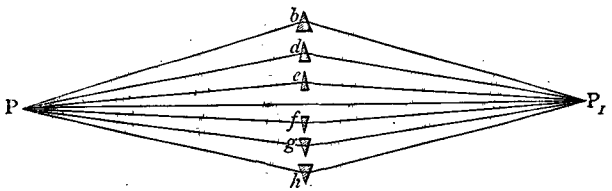


Fig. 59.

"meniscus;" it has a concave and a convex side, but the convexity exceeds the concavity, and so the lens is thickest in the middle. All these lenses are "con-

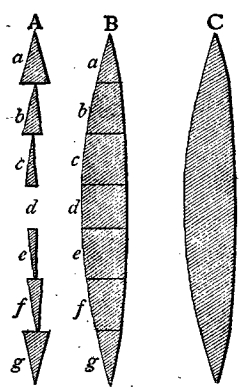


Fig. 60.

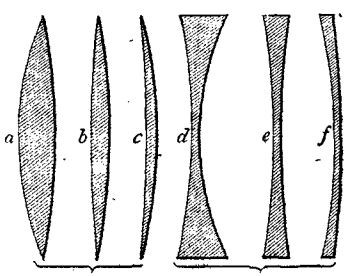


Fig. 61.

vergent." Rays falling on them are converged or brought together.

Lenses which are thinnest in the middle are "divergent," as rays falling on them are bent outwards, away

from the centre. Of these *d* is a double concave, *e* plano-concave, and *f* concavo-convex, the concavity exceeding the convexity.

To whichever class a lens belongs, its action may always be explained by similar reasoning to that previously employed, considering it as an assemblage of prisms.

With any convex lens, such as that shown in fig. 62, it will always be found that parallel rays falling upon it are refracted close to a certain point, which is called the principal focus—a point which with the glass of which lenses are most commonly made does not differ very

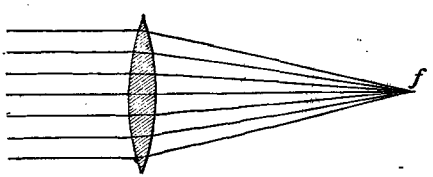


Fig. 62.

greatly from the centre from which the curve of the lens is struck. If one point of a pair of compasses be placed upon *f*, fig. 62, the other point can be swept round over the line marking the edge of the lens. Conversely also, if any source of light be placed at *f*, the rays will be rendered parallel[1] after their passage through the lens. Rays coming from the sun (or indeed from very much smaller distances) are sensibly parallel, and so when they fall on a burning-glass they are brought to a focus at the principal focus of the lens. On the other hand, in light-

[1] We had an instance of this use of a lens in the spectroscope, p. 86.

houses lenses are used to form a parallel beam of light out of rays diverging from the lamp. One great advantage of the electric light for lighthouses is that it radiates from a very small surface, the whole of which can practically be brought into the focus of the lenses, whereas the large oil flames extend quite beyond the range of the focus.

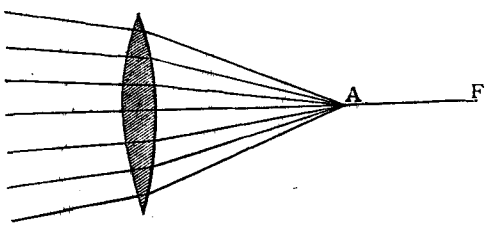


Fig. 63.

If a source of light such as a lamp be moved from the principal focus in towards the lens, as to a point *A* in fig. 63, the rays after passing the lens will diverge more than they did before. If the lamp is moved away from the principal focus, as to a point *P*, fig. 64, the rays will

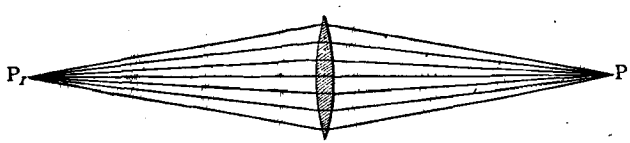


Fig. 64.

converge, and the point $P_1$ at which they meet will approach nearer and nearer the principal focus, which they will reach when the lamp has been so far moved away that the rays from it are practically parallel. Every point, therefore, along the axis of a lens has another corresponding point on the other side of the lens, to which all rays

starting from the first point will be converged, and from which all rays must come which are converged at the first point. Any two such pairs of points are known as *conjugate foci*.[1]

By extending the same principle a little further, we are enabled to see how images are formed by lenses, and how the relative sizes of the object and its image depend solely upon their relative distances from the lens. The rays from every point of the object are brought to a focus at a corresponding point on the other side of the lens, and an image is there formed capable of being received on a screen, and therefore a *real* image. This image may be, of course, of the same size as the object, or greater

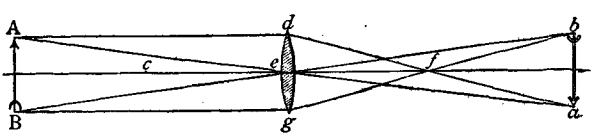


Fig. 65.

or smaller than it. It will be the same size if it is placed at a distance from the lens equal to twice the focal length. This case is represented by fig. 65, in which $c$ and $f$ are the principal foci of the lens, $A\ B$ the object, and $a\ b$ the image. The ray $A\ d$ will be refracted to $a$, to which point also the ray $A\ e$ will come, after passing through the centre of the lens, and suffering no refraction. Similarly, all other rays from $A$ which fall on the lens will be brought to $a$. In like manner, rays from $B$ will be focussed at $b$, and rays from all points between $A$

[1] The reader will note the similarity between the action of curved mirrors acting by reflection and lenses acting by refraction. See p. 36, *ante*.

and $B$ at corresponding positions between $a$ and $b$, and we shall have at $a\ b$ an inverted image of $A\ B$, of the same size, and at the same distance from the lens on the other side of it.

Shift the object further away, as in fig. 66, and the same construction will show us that we get a smaller

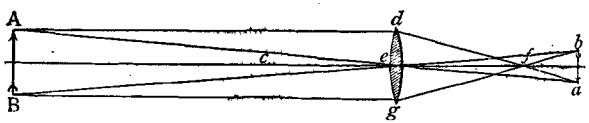


Fig. 66.

image nearer the lens. Bring it closer in, and we get a larger image, further away from the lens, as in fig. 67. The former case illustrates the action of the photographic camera, in which a picture of a distant object is formed on a screen close to the lens, the latter (fig. 67) that of the optical, or "magic" lantern, in which a picture on a

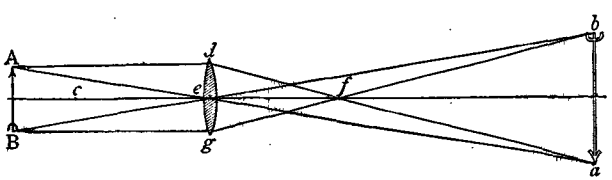


Fig. 67.

small scale close to the lens is reproduced on a greatly magnified scale on a screen some distance off.

If we move the object still closer to the lens, till it occupies the position of the principal focus, all the rays starting from it will be rendered parallel, and no image will be formed. Nor will there be any real image if the object is placed between the principal focus and the lens.

In that case the rays will be rendered still more divergent than they originally were, and, as shown in fig. 68, they appear to an eye placed behind the lens, to start from points in the line *a b*, and therefore present to the eye an enlarged image of the object. We therefore say that the lens forms at *a b* a *virtual* image of the object *A B*. This is the case of the ordinary magnifier, which has to be brought close to the object, when it presents to the eye on the other side of it an enlarged image of the object.

It is easy to reproduce all the above cases with a

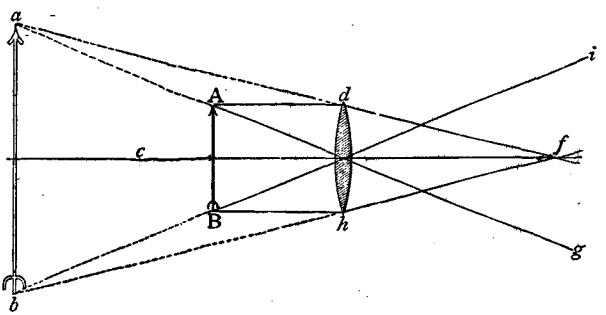


Fig. 68.

common pocket lens. Place such a lens close above the letters on a printed page; on looking through it from a convenient distance the letters are seen magnified. Move the lens away from the page and the letters will disappear (when they are at the principal focus of the lens), but will soon reappear, still enlarged, but upside down. This is the case of fig. 67. Now move the head back from the book and bring the lens a little nearer the eye; the type will seem to get smaller, till it is about the actual size (fig. 65), and then to diminish till it becomes quite minute (fig. 66).

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The simple double convex lens, *a* in fig. 61, is the commonest form, but the action is just the same with any of the lenses which are thicker in the middle. The amount of refraction, and consequently the position of the focus, will differ according to the curves of the lenses, but they will all act in the same manner, and consequently, as stated above, they are all termed *convergent* lenses.

With lenses which are thinner in the middle, precisely the opposite set of conditions exists. It is as though we were to turn all the prisms of which we may consider a lens constructed, the other way round. They will then

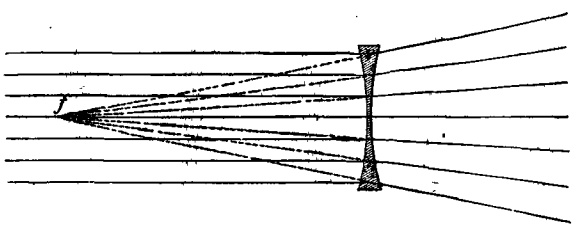


Fig. 69.

serve to scatter the rays outwards, and are therefore termed *divergent*. This term is equally correct for any of the three typical forms given in fig. 61, and we may therefore content ourselves with the consideration of the simplest form *d*, in which the two sides are similar, the double convex. Fig. 69 represents parallel rays of light falling on such a lens. They are, of course, rendered divergent, and they will appear to diverge as from a point *f*, which is, though not quite correctly, termed the principal focus. Sometimes it is called the negative focus. If the rays are already divergent when they strike the lens, they will be rendered more divergent

still. In no case, therefore, can any real image be formed by a lens of this class.

A concave lens, however, can always produce a virtual image. If $A\,B$ be an object looked at through a lens $c\,h$, the ray $A\,c$ will be refracted to $d$, and will appear to come from the direction $f\,a\,d$; the ray $A\,e$ will pass through the centre of the lens unrefracted to $g$. As the two lines intersect at $a$, the rays will appear to start from $a$. So rays originating from $B$ will appear to start from $b$, and we shall have a virtual image $a\,b$.

In the present chapter we have been considering lenses

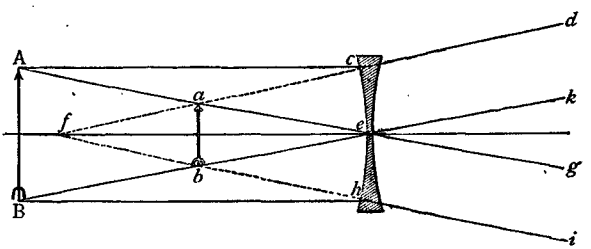


Fig. 70.

as if their action in practice were identical with their theoretical action. This however is far from being the case. We have had for the sake of simplicity to make a number of assumptions, in order to get at the fundamental principles which govern the working of all lenses. Unluckily, when we try to reduce these principles to practice, we find that they are hedged round with limitations, and that the subject is far more complicated than we might have thought. Still, the only way of arriving at a clear comprehension of the whole is to try and get a mastery of the various portions separately. If we

endeavour to grasp the whole at once, we shall find ourselves baffled and confused by a mass of detail, which will so obscure the main principles that we shall certainly fail to appreciate them at all.

Now we have assumed that a lens, when it brings rays falling on it to a focus, brings them all to absolutely the same point. This, however, is not the case. If we go back to our original conception of a lens as an aggregation of prisms, we shall at once recognize the fact that it must possess that special attribute of prisms, the power of

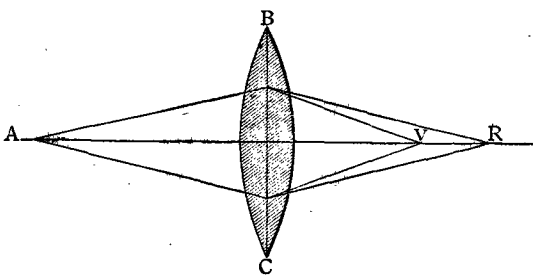


Fig. 71.

decomposing or dispersing the light. It is true that a lens is equivalent to a very sharp-angled prism, and consequently the dispersion will be but moderate, yet still it exists. The rays proceeding from a luminous source *A*, and falling on a lens *B C*, will be decomposed, and the violet rays will, as they are more refrangible, be focussed at *V*, nearer to the lens than the point *R*, where the red rays will be brought to a focus. The result in practice will be that at *V* we shall get an image with a bluish fringe, and at *R* an image with a red fringe. This defect in lenses is termed chromatic aberration. Newton,

when he investigated this point, arrived at the conclusion that the amount of refraction and the amount of dispersion were proportional, and that, as it was impossible to get one without the other, the defect was incurable ; in other words, that an achromatic object-glass, or a glass not showing these coloured fringes, was impossible. Here, however, the great philosopher was mistaken. Later researches showed that in different substances the proportions between the dispersive and the refractive powers may vary considerably. Thus, flint glass has very much more dispersive power than crown glass. Hence it becomes possible, by combining a convergent lens of one glass with a divergent lens of the other, to eliminate the dispersion and yet leave a considerable though diminished amount of refraction. By this means achromatic lenses are constructed.

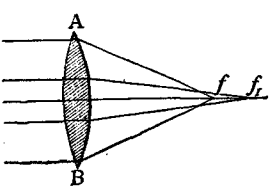

Fig. 72.

The first to make an achromatic lens is believed to have been Chester More Hall, about 1730, but his invention was not published at the time, and the practical introduction of the method was due to Dollond in 1757.[1]

Another aberration of importance is spherical aberration, because it is due to the spherical form of the lens. Rays near the edge of any convergent lens are brought to a focus rather nearer the lens than rays at the centre, as is shown in fig. 72, where it is evident that the focus of the lens really extends along the axis from $f$ to $f_1$. This aberration can be cured in the same way as chromatic aberration, by combining with the convergent lens

[1] Grant, *History of Physical Astronomy*, p. 533.

a divergent one of suitable form; and fortunately it is possible to effect this by the same lens which serves to correct the chromatic aberration, the shape of each one of the pair of lenses being carefully calculated for the purpose. By the application of this simple but beautiful device, all lenses or combinations of lenses used for optical purposes are corrected.

## CHAPTER VIII.

### OPTICAL INSTRUMENTS.

Microscopes.—Telescopes.—Erecting Eye-piece.—Opera-glass or Galilean Telescope.—Reflecting Telescopes.

INSTEAD of receiving the images formed by lenses direct into the eye, we may treat these images themselves as objects, and magnify them again by another lens. If we magnify the image formed as in fig. 67, we shall have a rudimentary form of compound microscope. By magnifying the image of fig. 66, we shall have a crude form of telescope. These statements may easily be verified with a couple of magnifying glasses. The construction of the microscope is shown in fig. 73; $c$ is the lens which forms an image of the object, and is therefore known as the object-glass; the object being represented by $a\,b$, the image will be $a_1\,b_1$. This image is again magnified by the lens $d\,e$, which forms a virtual image at $a_2\,b_2$. This lens is termed from its position the eye-piece. It seems hardly necessary to say that in microscopes of however common construction, the lenses both of object-glass and eye-piece are not of the simple character indicated in our sketch. They are actually combinations of lenses. Still, however elaborate they may be, they act theoretically precisely as the pair of simple lenses; their action may in

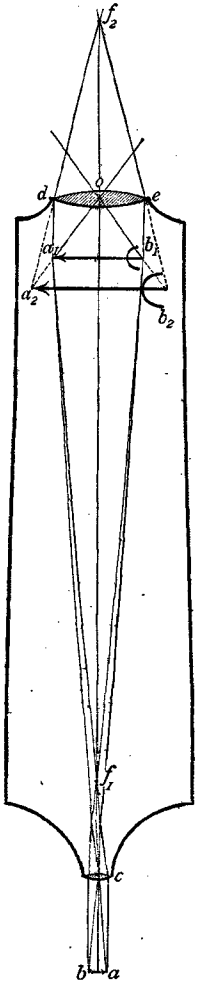

Fig. 73.

theory be reduced to that of the two simple lenses by which they are here represented.

Fig. 74 shows us the form of telescope obtained by adding a magnifying lens to fig. 66. The rays coming from a distant object fall upon the object-glass *c d*, and the larger this is the more light will be received and the brighter will be the image. These rays form the image $a_1 b_1$, which is magnified by the eye-piece *e g* into the virtual image $a_2 b_2$. Now it will be noticed that this image is inverted, and therefore this sort of telescope is only used for astronomical purposes, for which an inverted image is not a great drawback. For ordinary purposes a third lens is introduced, as shown at *h i* in fig. 75. This, as will be seen by following out the course of the rays as indicated by the lines, inverts the image again, and so presents it in its proper position to the eye. An "erecting eye-piece" is a usual addition to astronomical telescopes, to fit them for terrestrial use.

There is also another form of telescope, one of the earliest of any, for it was invented by the great Galileo, and is called after him the Galilean. It survives in the modern opera glass, where great magnifying power is not

required. Fig. 76 shows the construction: *c d* is the object-glass, the rays falling on it at *h i* and *k* would form an image as usual, but they are intercepted before they can do this by the concave lens *e g*, and are rendered more divergent by it. The ray *i l* is refracted to *r*; the ray *k m* to *s*. So also the ray *i q* is refracted to *u*, and the

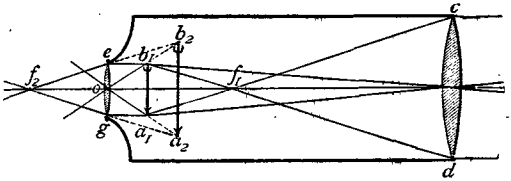


Fig. 74.

ray *h n* to *t*. The result is that an erect virtual image is formed at $a_2 b_2$. In this case, therefore, we get an erect image with only two lenses.

Before quitting the subject of telescopes, it may be well just to refer to the other important glass of these

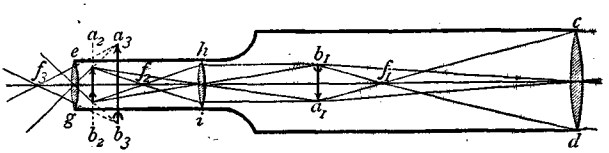


Fig. 75.

instruments, in which mirrors are used. These are known as reflectors, in contradistinction to those in which, as we have seen, the image is formed by a lens, and which in consequence are called refractors. The Newtonian, named after its great inventor, may be taken as the type of these. It is illustrated in fig. 77. The

mirror $c\,d$ would form an image of the distant object at $b_1\,a_1$, but this could not be viewed by the observer, whose head would of course screen the mirror. A small

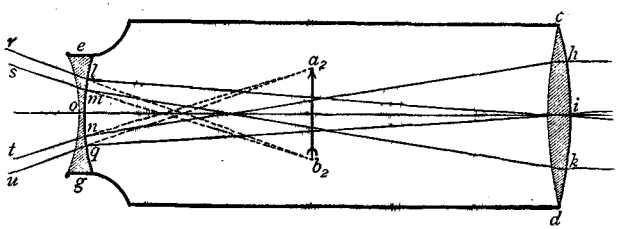


Fig. 76.

flat mirror is therefore introduced at $s\,s$, and by it the rays are turned at right angles and out through an opening in the side of the telescope, in which the eye-piece $e\,g$ is fitted, and by this they are viewed as in the instru-

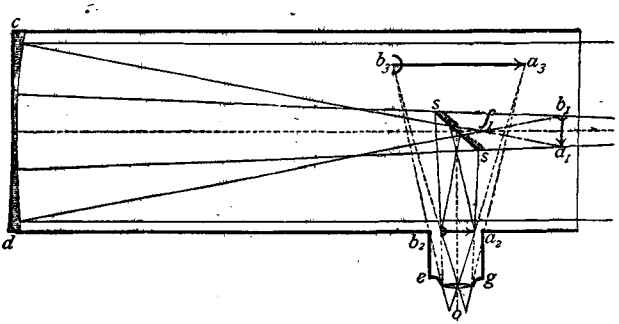


Fig. 77.

ments previously described, the image $a_2\,b_2$ being magnified into the virtual image $a_3\,b_3$.

Other devices have also been employed to enable the observer to see the image formed in the mirror without

himself obstructing it. In the Herschelian form the mirror is set a little on one side, inclined to the axis, so as to throw the image to the side. It can then be viewed by an observer looking down into the telescope.

Reflectors are only used for astronomical purposes, for which they have certain advantages. The mirrors in the older instruments were of metal. In modern reflectors they are of glass, silvered on the surface, to avoid double reflections.

## CHAPTER IX.

### DOUBLE REFRACTION AND POLARIZATION.

Double Refraction of Iceland Spar.—Explanation of the Phenomenon.—Tourmaline.—Nicol's Prism.—Polarization by Reflection.—Colours of Polarized Light.—Examination of Crystals by Polarized Light.—Uni-axial and Bi-axial Crystals.—Industrial application of the Polariscope.

THE phenomena resulting from the use of polarized light are certainly the most beautiful of any of the colour phenomena which can be produced experimentally, and the reason for this is, that by using polarized light we can very fully utilize the effects of interference. We can produce on a large scale experimental illustrations which, without its assistance, could only be shown on a very small scale, besides obtaining many others which without it could not be shown at all. Unfortunately, while it is easy to describe the phenomena, it is by no means easy to explain them in such a way as to make them readily intelligible without considerable study of the subject. Still, this part of the subject is so interesting, its results are so beautiful, and the bearing they have on the whole theory of light is so important, that it is well worth while to spend a little trouble in endeavouring to grasp at all events its elementary principles.

If a piece of Iceland spar be laid on a sheet of paper on which has been made a little round dot of ink, it will

be found that in every position of the crystal, except one, the dot will appear double. If the piece of spar be now turned round (twisted round as it lies on the paper, not turned over), one of the two images will be seen to revolve round the other one. Fig. 78 shows this, the path of the moving dot being indicated by the little circle. This is the phenomenon known as *double refraction*. A similar effect is produced when the spar is laid upon a printed page; the print appears to be doubled. Or if a piece be introduced between the lens of a lantern and the screen, the image formed on the screen will be doubled. There is, however, one direction through the crystal in which this doubling does not take place, the direction parallel to the optic *axis*, the imaginary line round which the crystal is symmetrically formed.

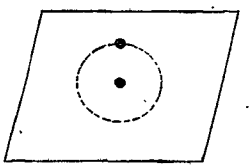

Fig. 78.

It is evident that the single ray of light has been by some means split up into two, and this is really what has happened. Fig. 79 illustrates this. A ray of light starting from *A*, when it impinges on the surface of the crystal at *a*, splits into two rays, one of which pursues a nearly straight course through the crystal, passing out at *b*, and so on to *B*; while the other has been more refracted, so that it emerges at *c*, and passes on to *C*.

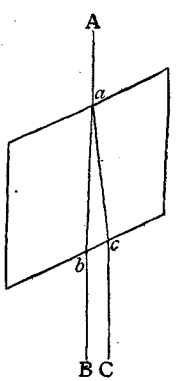


Fig. 79.

This behaviour of the ray can only be explained by a reference to our fundamental theory of light, and the

phenomenon itself offers one of the strongest pieces of evidence in favour of the undulatory theory. To understand what has happened, even to get an elementary notion of it, we must advance a little further in our conception of the nature of light. Hitherto we have been content to regard light merely as a wave motion, without inquiring as to the nature of the wave, or the character of the motion of the particles which produce the wave. It is evident that there may be a great variety of movements which in their combination produce a wave. The particles may move in straight lines up and down, or right and left (these movements, or any intermediate movements, will all be *transverse* to the direction of the wave-motion), or they may move to and fro in the line of the path of the wave itself (*longitudinally* to its direction), or, while vibrating in planes transverse to the direction of movement, they may move in circles or ellipses, or in paths changing gradually from one figure to the other.

Waves in water may, for present purposes, be considered as examples of the first class, waves of sound are instances of the second. It is believed that light waves are produced by motions of the third class. This, however, is a portion of our subject with which we cannot further deal; suffice it to say that we must consider the particles of ether as vibrating *transversely* to the direction of the wave, and in every possible direction in a plane at right angles to the path of the wave, that is to say in all azimuths in that plane. This idea may be crudely illustrated by fig. 80, which is intended to show the paths of the particles in a wave whose path is at right angles to the plane of the page of the book.

Now the structure of the crystal is such that, except for waves following the line of the optic axis, the particles of ether within it cannot vibrate with equal freedom in all azimuths, but only in two, at right angles to each other—as we might say, up and down, or right and left. Consequently all the vibrations are resolved into these two classes. And those which vibrate in one direction—say, up and down—pass more easily through the crystal than those vibrating right and left, so that the former pass on

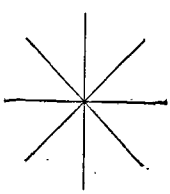

Fig. 80.

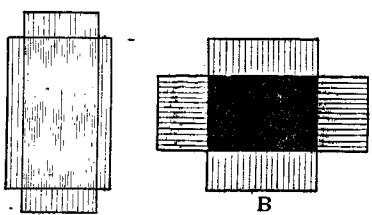


Fig. 81.

with little refraction, while the latter are retarded and are more refracted. These rays are then said to be "polarized,"[1] the more refracted in this case being termed the *ordinary* ray, the less refracted the *extra-ordinary* ray.

The mineral tourmaline has the property, not only, like Iceland spar, of polarizing light, but also of absorbing one of the rays polarized, so that it suffers only a single ray to pass. If this ray fall upon a second plate of tourmaline, set with the planes of polarization in the same direction (as if the two plates were forming part of one crystal), it

[1] The word *polarization* has really no meaning as applied to light. Newton first employed it, it appearing to him that the rays had sides, corresponding to some extent to the poles of a magnet.

will pass through, but if the tourmaline be set with its crystalline structure in the opposite direction, the ray will be stopped. Fig. 81 represents the shadows cast on the screen by a pair of tourmalines. In *A* they are placed in like positions, and there is only a slightly darker shadow where the light passes through both, from the absorption by the colour of the mineral. In *B* one of them has been turned through a right angle; they are in opposite positions, and no light can pass.

The reason for this is evident. All the vibrations having been brought into one plane, the wave can only pass through material which permits the passage of vibrations in that plane. Imagine a grating of upright parallel bars. A pendulum swinging in a direction at right angles to the face of the grating could be passed between the bars without any interference with its swing, but if it was swinging in a plane parallel with the row of bars, its movement would be stopped by an attempt to push it between them. So with the tourmaline. The second tourmaline in *A* may be regarded as a grating with its bars parallel to those of the first, so that the swinging particles can transmit their movement. In *B* the second tourmaline may be considered to have its bars turned across the direction of those of the first, so that all passage is prevented.

For experimental purposes it is desirable to have some arrangement by which, as in the tourmaline, only one of the two polarized beams is transmitted, so that it can be examined separately. Tourmaline, being brown or green in colour, only lets through a portion of the light which falls upon it, and this is an obvious disadvantage, while the Iceland spar does not separate the two rays sufficiently

widely for them to be conveniently dealt with. There is, however, an ingenious arrangement known as a Nicol's prism, which answers the purpose perfectly. Such a prism is represented diagramatically in fig. 82. The crystal is cut in two by a line drawn from the angle at *d* to the angle at *e*, and the two parts are cemented together with Canada balsam. In consequence of the different extent to which the ordinary and extraordinary rays are refracted, and also because of the different angles at which they strike the film of balsam, the ordinary ray *A a c* is totally reflected, and turned aside, while the extraordinary ray passes on with little or no hindrance and out at the other end of the prism.

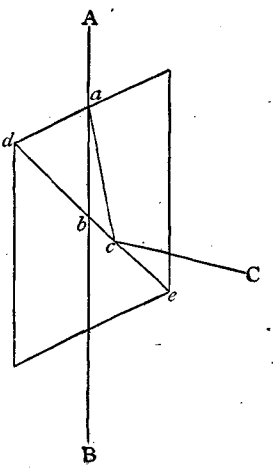

Fig. 82.

As with the tourmalines, rays which have passed through one Nicol will pass through a second, set in the proper position, but if either Nicol be turned through a quarter of a revolution [1] the light will be entirely quenched. It is therefore possible to tell at once, by examination with a Nicol, whether any light is polarized or not. For it should be noted that the eye has no

[1] In this position the Nicols are said to be "crossed." The one through which the light first passes is termed the "polarizer," the second, through which the eye examines the light polarized by the first, is called the "analyzer." Every complete polarizing apparatus includes a polarizer and an analyzer.

power of distinguishing between light which has been polarized and light which has not.

If any ordinary light be looked at through the prism, it will be transmitted equally brightly (though with generally diminished brightness) in whatever position the instrument may be placed, and turning it round on its axis will make no difference whatever; but if the light be polarized, it will appear bright only when the Nicol is in one position; on turning the instrument round the light will get dimmer, till after a quarter of a revolution it will be very dull, or may even have disappeared entirely. Continue turning, and the light will brighten again, to grow dim and again bright before it has returned to its original position.

And very much of the light in nature is polarized, for polarization can be effected by reflection as well as by refraction. Light falling on glass at an angle of 58°[1] with the perpendicular is completely polarized, so it is if it fall on water at an angle of 52° 30′. Light from the sky is always partly polarized. If the light reflected from almost any polished surface (except a metallic surface) be examined with a Nicol, it will be seen to be more or less polarized, that is to say, some of it is polarized, but it is mixed with a proportion of unpolarized light.

On this principle a very efficient polarizing apparatus has been constructed, in which two mirrors of unsilvered glass are used, one as the polarizer, the other as the analyzer. When they are set as in fig. 83, the second reflects the ray which has been polarized by the first, but if the second be turned round through a right angle on a vertical axis passing through its centre, it will be found

[1] The angle varies with the description of glass.

that no reflection at all takes place; the polarized light is incapable of reflection, except in the plane in which it was polarized. All polarizers are, it may be mentioned, interchangeable. An inclined mirror may be used to test the light polarized by a Nicol or any other similar piece of apparatus, just as the Nicol was used to test light polarized by reflection.

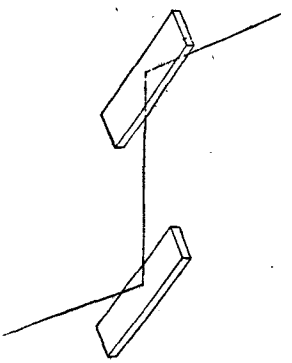

Fig. 83.

Yet another form of polarizer is made by fitting a number of thin sheets of glass close together in a tube, at such an angle that light falling on them is polarized; for not only is the reflected ray thus affected, but the transmitted. This serves precisely the same purpose as the Nicol.

Supposing we have a complete polarizing apparatus

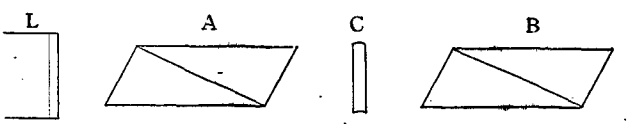


Fig. 84.

arranged as in fig. 84, in which *A* represents the polarizer and *B* the analyzer, *L* being the source of light. On the small scale the experiment may be viewed by the eye, on the large the effects may be projected upon a screen, so as to be seen by many persons at once. Let the Nicols be crossed, so that no light gets through. Then

introduce between the two at *C* a sheet of mica, or selenite, or a piece of some other doubly refracting crystal. A position for the mica or other crystal will be found at which it enables the light to pass, and the field, previously dark, will be illuminated, as if the Nicols had been set in the same position. This perplexing result is capable of a quite simple explanation. The mica must be set with its polarizing planes inclined to those of the Nicols. The polarized ray emerging from the first Nicol, when it strikes the mica, will be resolved into two rays in planes at right angles to each other. These, as they reach the second Nicol, will again be resolved into waves capable of passing through it, of which one will be reflected away while the other passes through.

Perhaps a rough sketch may make this clearer. *A* (fig. 85) is to be taken as representing the planes of vibration of the rays in the first Nicol, the dotted line indicating the plane belonging to the ray which is lost; the emergent ray, to get through the mica, must resolve itself into two, in the directions shown at *B*. These again, to get through the second Nicol, must resolve themselves into the two shown at *C*, and of these, one is abolished, but the other emerges.

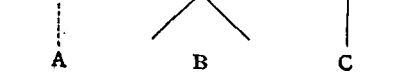

Fig. 85.

Further than this, if the thickness of the mica be such as to cause one of the transmitted rays to lag half a wave length, or any odd number of half wave lengths of any colour behind the other ray, though the rays cannot indeed interfere with each other so long as they are vibrating in

different planes, yet when they are combined by the analyzer they will interfere, and we shall get colour. Turning one of the Nicols a quarter turn the colour disappears, and white light is produced, turning yet another quarter, and the colour complementary to that first seen becomes visible.

The colour will of course depend on the thickness of the film, and if the mica or selenite be of varying thicknesses we shall have a corresponding variety of colours. By selecting thin films of mica, such as can be split off from an ordinary sheet of the mineral, and superposing them one upon another, variegated patterns can be constructed; or by scraping away the mica in places, designs can be made. These, which in ordinary light have the usual transparent look of the mineral, will, in the polariscope, glow with most gorgeous interference colours.[1]

Many crystals when examined in this way show vivid colours, and there can be few spectacles showing a more splendid play of colour than is presented when the crystals are caused to form themselves on a piece of glass in the polariscope. This spectacle can be enjoyed by the possessor of any microscope who likes to get it fitted with a simple polarizing apparatus, or will go to the trouble of fixing a small Nicol in a cork below the stage of the instrument, and another in the tube which carries the eye-piece. It is very easy to get a saturated solution of a salt to crystallize on an ordinary microscope slide, and the effect is quite as good as when the process is shown

[1] Full instructions for the production of these patterns will be found in Lewis Wright's book on "Light."

on a large scale, by means of the projecting lantern and a screen.[1]

And not only most crystals, but many other bodies show interference colours when viewed by polarized light; even organic bodies, such as horn, shell, hair, scales, fibres, etc., can thus be made to give chromatic effects. Some bodies which in their normal state have no doubly-refracting capacity can be endowed with it by subjecting them to stress. By this means their molecular structure is affected, and the polariscope detects the alteration. It is a favourite experiment to place a block of glass in the polariscope, and then to compress it strongly by means of a screw, when brilliant colours will at once appear. Similar effects are exhibited by pieces of glass which have been unequally annealed, so that they are in a state of internal strain.

A special and important application of the polariscope is to the examination of crystals, and by its use much information about crystalline structure has been obtained.

For instance, when a plate of a crystal of the class known as uni-axial,[2] or having only a single optic axis, is examined by convergent light in the polariscope, if the plate has been cut at right angles to the axis, an appear-

[1] Dr. Carpenter, in his book on the Microscope (p. 766, chap. xx., of the edition of 1862), gives very clear directions as to the best way of operating. He also adds a list of the most suitable crystals.

[2] Without entering into details which would carry us beyond the scope of our present subject, it may be convenient to mention that crystals belonging to the system known as the "cubic" behave as homogeneous media, showing no effects other than would be shown by glass; "pyramidal" and "rhombohedral" crystals have a single optic axis, and behave generally like Iceland spar, while crystals of the "prismatic," "oblique," and "anorthic" systems are bi-axial.

ance like one of the two forms in fig. 86 will be presented. In A the Nicols are crossed, in B they are not crossed; the black and light crosses in the figure are due to the fact that in those planes there is no double refraction, and the light therefore is simply transmitted, or not transmitted, according to the relative positions of the Nicols, whereas in all intermediate planes double refraction does take place, and consequent interference.

Bi-axial crystals give figures of much greater com-

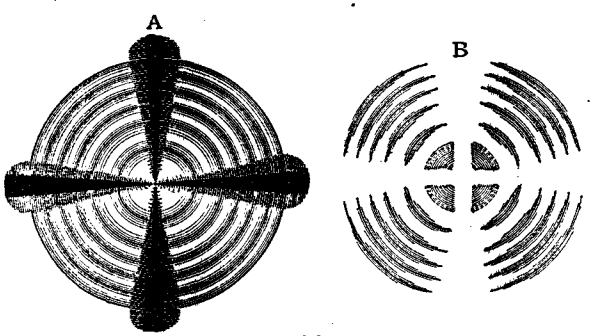


Fig. 86.

plexity, and the polariscope therefore affords a means for distinguishing one class from the other.

The polariscope also has its industrial applications. It serves to test the character and strength of saccharine solutions, which vary in their effect on polarized light according to the amount of sugar they contain. An explanation of the principle on which such tests depend would involve a discussion of the phenomena of "circular polarization," a very difficult part of the subject to treat in an elementary fashion, so the mere mention of the fact must suffice.

The experimental study of this portion of the subject of optics is most attractive. The apparatus required is neither elaborate nor costly, while the effects that can readily be produced are most fascinating. It may be admitted that, as an instrument of research or education, the polariscope cannot claim a place in the first rank of optical instruments, but as a source of intelligent amusement, and as affording examples of the hidden beauties of nature, it is hardly second to any.

## CHAPTER X.

### CHEMICAL EFFECTS OF LIGHT.

Changes effected by Light.—Extent of the Spectrum.—Effects of Light on various substances, bitumen, bi-chromatised gelatine.—Salts of the metals.—The Silver Haloids.—Photography.

UP to the present we have been concerned only with the effects of light upon the eye as producing vision. It remains to devote a little attention to the other effects of light—effects equally important, though less obvious to our senses. That many, probably most, and possibly all substances are affected by the impact upon them of those radiations which when they fall upon our eyes we recognize as light, is certainly true. To a large extent, it is a matter of common knowledge. We know that plants protected from the light are blanched, that in the absence of light they have no power of producing the green colouring matter of their leaves. We know that many colours fade when exposed to light. We know that photographs are taken by the action of light—that textile fabrics can be bleached and our own skins tanned by the same means.

These are but a few of the changes which are due to the chemical action of light, the power it possesses of altering the actual constitution of bodies, decomposing

them, and producing fresh combinations of the original elements.

One important fact that we soon discover, when we try to investigate the chemical action of light, is that it is not only the light which is perceptible to our eyes that effects the changes in question. We find that there exist far beyond the limits of the visible spectrum, rays which are equally powerful as regards their effects on inert matter. Our eyes, indeed, have only the power of perceiving about a third of the spectrum as it is at present known. The researches of Abney in this country and of Rowland in America have proved the existence of rays extending below the red rays to a distance at least equivalent to the whole length of the visible spectrum, and beyond the violet they are known to extend to a greater distance still. The rays at and beyond the violet end of the visible spectrum were at one time known as the chemical or actinic rays, because it was thought that they alone had the power of producing chemical changes. It is now known that this view is incorrect, though it is true that the rays at the more refrangible end are the most active. There are, however, substances which are most sensitive to the less refrangible rays, as there are others which are sensitive to the violet end alone.

The changes produced by light are many and various, and the causes of very many of them are still quite unknown. If a tube containing chlorine and hydrogen gases be exposed to strong light, the gases will combine with explosive violence, though in the dark they will remain without any action on one another. Certain varnishes if exposed to light become insoluble in their

ordinary solvents. If a film of a bituminous varnish[1] be spread on a plate of glass or metal, and when dry exposed under a pattern cut out of black paper, or something of the sort, to bright sunlight, it will be found that the varnish can be washed off with turpentine where it was protected by the paper, but that the parts on which the sun has acted have become insoluble, so that, if the operation be carefully performed, we shall have a facsimile of the original pattern. This was, in fact, the way in which the first permanent photographs were obtained, and the process is now used for the production, by photographic means, of printing plates and blocks for books and newspapers.

Again, if a solution of gelatine to which a little bichromate of potash has been added be spread upon paper, and the paper exposed under a pattern, the parts where the light has acted will become insoluble in water,[2] and when the paper is wetted they will remain unaffected, while the protected parts will absorb water, and will swell up, so that we get a copy in relief of the original. Or, if the paper be treated with hot water, the soluble parts can be washed away, while the insoluble remain, thus giving a reproduction of the pattern in gelatine. If, in addition to the bichromate, a little colouring matter has been added to the gelatine, we get a coloured picture. Here again we have the basis of many and very important photographic processes.

A photograph—of a sort—may be produced by even

[1] The varnish sold under the name of "Liquid Jet" answers extremely well.

[2] These statements are also true of many colloid substances in combination with an alkaline bichromate.

simpler means; by simply exposing under a pattern a piece of paper stained with one of the common aniline dyes (or the coloured juice expressed from the petals of flowers) for a sufficient time—say the whole of a summer day—to cause the unprotected parts to fade. By this means we may get a copy which will last for years if kept out of strong light. And even in this simple experiment we get a suggestion of a practical photographic process, since an aniline dye has quite recently been discovered which is so affected by light as to lose its power of combining with certain other chemical reagents, which in combination with it produce various beautiful colours; so that when a pattern has been printed by light on a piece of fabric dyed with the compound, the fabric can be dipped into the appropriate solution, and it at once takes the colour desired in the parts where no light has been, the rest of the piece remaining unaffected by the solution.[1]

Of the various chemical effects of light, however, those of the greatest practical importance are its effects on certain metallic salts, certain compounds of metals with other elements, since it is on the changes brought about by light in these compounds that the ordinary processes of photography are based.

Of the metallic salts which are sensitive to light, the most sensitive, so far as is known at present, are some of the salts of silver—combinations of silver with chlorine, bromine, or iodine, that is to say, the chloride, bromide, or iodide of silver. In the last century it was noticed that silver

[1] See the paper describing the process, by the inventors, Messrs. Green, Cross, and Bevan, in the *Journal of the Society of Arts*, January, 1891.

chloride was blackened by light, and early in the present attempts were made to produce pictures, or, at all events, copies of opaque flat objects, by this means. The difficulty was that, when the picture was exposed to light, the light, acting on the parts previously protected, reduced them to the same condition as the portions previously blackened. For a long time all endeavours to find some solvent which would dissolve out the white unaffected salt, without dissolving the blackened salt, were fruitless, but at last it was found that hyposulphite of soda had this effect. The power thus afforded of reproducing outlines by purely chemical means naturally led men to regard as possible the realization of the ancient dream of fixing the images of the looking-glass or the camera obscura. Nobody, indeed, who had studied the subject, ever believed that the reflections in a mirror could be fixed, for, as we have seen, there exist no real images to fix; but the notion of obtaining pictures by means of the camera obscura seemed, as it eventually proved, a perfectly reasonable one.

The process above hinted at was, however, far too slow, for the salt was not sufficiently sensitive to light to register the comparatively faint differences of light and shade which make up the image of the camera obscura, and it was not until a far more sensitive method was discovered that the problem was solved. It was found that not only are the silver salts visibly affected by a sufficient exposure to light, but that a much briefer exposure will bring them into such a condition that they are ready to be reduced, by suitable treatment, to the metallic condition.[1]

[1] Or, in the case of the daguerreotype process, to a condition in

The details of photographic manipulation are now very generally known, so popular has the process become, and if they were not, the scope of this treatise would hardly permit much treatment of them here. For the taking of the photographic negative, the "haloid"[1] salts of silver are now alone employed, that is to say, the combinations above referred to, of silver with chlorine, bromine, or iodine. Sometimes one of these salts is used alone, but more usually a mixture of two, or even of all three is employed. Till recent years the salt was embodied in a film of collodion, but it was found that if gelatine was used as the vehicle, a compound much more sensitive to light was formed, and except for certain special purposes gelatine plates are now always employed.

When a glass plate bearing on it such a film is exposed in a photographic camera, an image of the scene in front of the lens is of course thrown upon it. The brightest lights of the picture act on the salt with the greatest vigour, while the deepest shadows affect it very slightly or not at all. Thus is formed what photographers conveniently but a little illogically term the "invisible image." The plate, on its removal from the camera, or at some subsequent time—for the action of the light is permanent—is submitted to the action of the "developer," a liquid containing an agent having a strong reducing action, that is to say, tending to reduce the silver salt to the metallic state. The product formed

which they more readily combine with another metal, mercury, which is deposited on the parts where light has been.

[1] *Haloid*, from the Greek ἅλς, (*hals*), the sea, these salts being present in sea water.

in the film by the action of light is much more easily reduced than the unaltered salt, and the result is that the invisible or latent image is transformed into an image in metallic silver, which—as it is strengthened by the addition of further silver from adjacent parts of the film —is perfectly visible.

To complete the picture it is only necessary to dissolve away the unaffected portions of the salt, and this is done by what is known as the "fixing" agent, nearly always the hyposulphite of soda first used for the purpose. We then have a picture in which the lights are represented by a deposit of silver, and the shadows by bare glass, the intermediate gradations being also properly given by intermediate grades of opacity. We have thus what, when viewed by transmitted light, we term a negative. If, however, the deposit of silver be quite white (or if we whiten it, as can easily be done by treatment with a suitable chemical), and we place a black surface behind the plate, we then have the same picture as a positive, the lights showing light, and the dark parts dark.

From the negative we can obtain any number of positive copies by simply placing behind it a sheet of paper coated with a sensitive compound. The light passing through the transparent parts of the negative will then affect the paper below, while the parts below the opaque portions are protected from its action. For this purpose we can either use a compound which is blackened by lengthened exposure to light, such as the mixture of chloride and nitrate of silver on albumenized paper, which produces "silver prints," or a compound which gives a latent image with a shorter exposure, requiring development.

In printing processes, therefore, there is much more latitude, and any substance capable of being affected by light, however slowly, can be utilized.[1]

[1] Those who desire to follow up this interesting part of the subject, should consult Meldola's *Chemistry of Photography.*

## CHAPTER XI.

### FLUORESCENCE AND PHOSPHORESCENCE.

The ultra-violet rays.—Fluorescent substances: quinine, etc.—Phosphorescent substances.—Luminous paint.

THE fact has been mentioned above that the spectrum really extends far beyond the limits perceptible to our sight. Rays extending above the violet and below the red have been photographed, and their existence thus demonstrated, but this is not the only method by which they can be made obvious to our senses. If we place at the end of the visible spectrum a paper coated with acidulated sulphate of quinine, we shall see for ourselves that the spectrum does extend further than we before perceived it. The band of light will be extended, and we shall see beyond the violet a colour greyish-blue in appearance. If also a design be drawn with a solution of sulphate of quinine on paper it will, when dry, be quite invisible, but if the paper be photographed, the design will appear in the resulting picture, as if it had been drawn in ink, or it can be rendered visible by exposing it to violet light. Either the rays at the end of the spectrum, or light passed through violet glass will produce this result. The effect is indeed equally produced by white light, but our eyes can only perceive it when the

surrounding light has been diminished by cutting off all the rays except the dark rays at the end of the spectrum.

This effect is due to the phenomenon known as fluorescence, from fluorspar having been one of the first substances in which it was observed. Quinine is only one of many substances possessing this property; paraffin shows it, so does æsculin, a substance derived from the bark of the horse-chestnut, and chlorophyll, the green colouring matter of leaves, so too does the beautiful greenish-yellow glass containing uranium. These and many other bodies, when illuminated by certain of the rays of the spectrum in a darkened room, shine with a lustre of their own, each showing its own special colour, a colour not by any means the same as the natural colour of the body itself. This power has been shown to depend on the capacity which the various substances possess of absorbing certain rays of the spectrum, it having been proved that those rays which are absorbed are precisely those which excite the fluorescence. This can be demonstrated by passing light through two pieces of uranium glass. The first piece fluoresces, but the rays which have past through it produce no such effect on the second piece. The light has lost its power in the transmission, for the rays which would have produced the fluorescence have been absorbed. Moreover, the light which is emitted is not of the same colour as that which gives rise to the phenomenon. On the contrary, each fluorescing body has its own peculiar colour, whatever may be the colour of the exciting rays. Generally the exciting rays are of higher refrangibility than those emitted, and they may even, as we have seen, be rays beyond the violet.

By the very ingenious instrument known as the phos-

phoroscope, it has been shown that the fluorescence does last a short time, though a very short time, after the exciting light has been cut off, and in this respect it differs from the phosphorescence[1] shown by certain bodies, which possess the mysterious power of storing up light in themselves, and giving it slowly out. To a very limited extent, probably many bodies possess this power, but at present the only substances showing it in any perceptible extent are certain sulphides and chlorides. Of these, the sulphide of calcium is the principal; it is of this that the well-known "luminous paint" is composed. This is excited only by the more refrangible rays, and, like the fluorescent substances, when excited it gives off a uniform bluish light, not light corresponding in hue to that of the rays which have been thrown upon it. Not only is it not excited by the rays of lower refrangibility, those at the red end, but these actually destroy the effect of the blue rays if thrown upon it after the action has been aroused.

Other sulphides and chlorides have been prepared experimentally which show the same effect, though none to the same extent. These show considerable variety of colours after being illuminated, the same specimen always showing the same colour. Very little is known as to the real nature of the phenomenon and no cause for its production has yet been assigned.

[1] This phosphorescence has no connection with the substance phosphorus, or with the power of emitting light possessed by certain living creatures, and also by some decaying animal substances. Phosphorus emits light on account of its being slowly oxidized or burnt in the air. How fireflies, or the animalcula which give the phosphorescent appearance to the surface of the sea, produce their light is not known, nor has the cause why decaying fish glow with a phosphorescent shimmer ever been discovered.

# APPENDIX.

IT may be useful to the student to give the names of a few books by means of which he may carry on the study to which this little work is intended as an introduction. Only books of a quite elementary and popular character are included.

For practical instruction in Elementary Physics there are few books better than Weinhold's "Experimental Physics," English translation, by B. Loewy (Longmans, 1875). The detailed instructions given for the construction of simple apparatus are admirable. For the private student the book is invaluable. He may well commence by working through the chapters on "Light," carrying out the experiments in accordance with the instructions.

Another excellent practical book is Lewis Wright's "Light" (Macmillan, 1882). Mr. Wright is an authority on the projection lantern, and his experiments are mainly intended for public demonstrations, but there is a great deal of solid information in the book, very clearly and simply put. A second book by the same author on "Optical Projection" (Longmans, 1891) is entirely devoted to lantern work. It is to be recommended to those who make any use of the lantern, but will be less serviceable to beginners.

Lommel's "Nature of Light," International Scientific Series (King and Co., 1875), is a useful book, dealing with the whole subject in a popular way.

Professor Tait's "Light" (A. and C. Black, 1884) is not quite so popular in treatment, and it assumes an elementary knowledge of mathematics, but it is wonderfully clear, and will take the student at all events a little way on towards the more serious study of the subject.

Professor Tyndall's charming book on "Light" (Longmans, 1873) ought to be in the hands of everybody who studies physical science, in however *dillettante* a fashion. The student will appreciate it better if he comes to it with some knowledge of the subject. The beauty of the language, and the skill with which the subject is treated, make the book appear more easy and more elementary than it really is.

Guillemin's "Phénomènes de la Physique" (English translation by Mrs. Norman Lockyer, "The Forces of Nature") (Macmillan 1872) is a thoroughly popular work, and magnificently illustrated. A considerable section of the volume is devoted to Light.

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On the subject of *Colour* the following may be recommended:—

Professor A. H. Church on "Colour" (Cassell 1887), a clearly written elementary manual, quite sufficient for those who do not want to pursue the subject very far.

Rood's "Modern Chromatics," International Scientific Series (Kegan Paul, 1879), goes rather further into the subject, and treats it very thoroughly.

Von Bezold's "Theory of Colour," translated by S. R. Koehler (L. Prang, Boston, U.S., 1876), is valuable.

Abney's "Colour Measurement and Mixture" (published as this book is going through the press), Romance of Science Series (Society for the Promotion of Christian Knowledge, 1891), contains the results of much original and recent investigation.

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For the *Spectroscope,* perhaps the best books are the following:—

Norman Lockyer's "Spectroscope," Nature Series (Macmillan, 1873). This is quite an elementary work.

Norman Lockyer's "Studies in Spectrum Analysis," International Scientific Series (Kegan Paul, 1878).

Schellen's "Spectrum Analysis," translated from the German by the Misses Lassell, and (second edition) edited by Captain Abney (Longmans, 1885). It will be found very useful.

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The number of manuals dealing with *Photography* is endless.

Abney's "Treatise on Photography," Text-books of Science (fifth edition, Longmans, 1888), remains the best general book on the subject.

The various editions of the same author's "Instruction in Photography" (Piper and Carter, eighth edition, 1888) are the best practical treatises.

For the chemical side of photography Professor Meldola's admirable work on "The Chemistry of Photography," Nature Series (Macmillan, 1889), should be consulted.

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The subject of *Polarized Light* comes into all the text-books. It is treated apart in:—

W. Spottiswoode's "Polarization of Light," Nature Series (Macmillan, 1874), a very useful little work, but less popular in character than its talented author evidently desired that it should be.

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The question of *Vision* has been but very slightly dealt with in the foregoing pages. The student desiring information on this branch of the subject may consult either of the following:—

"Eyesight, Good and Bad." R. Brudenell Carter (Macmillan, 1880).

"Sight." J. Le Conte, International Scientific Series (Kegan Paul, 1881).

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Probably the best work on *Colour Blindness*, is that by Dr. Joy Jefferies (Houghton, Osgood and Co., Boston, U.S.).

A more popular introduction to the subject is R. Brudenell Carter's "Colour Blindness," a reprint of three lectures given before the Society of Arts in 1881 (Bell and Sons, 1881).

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